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The Proceedings OF THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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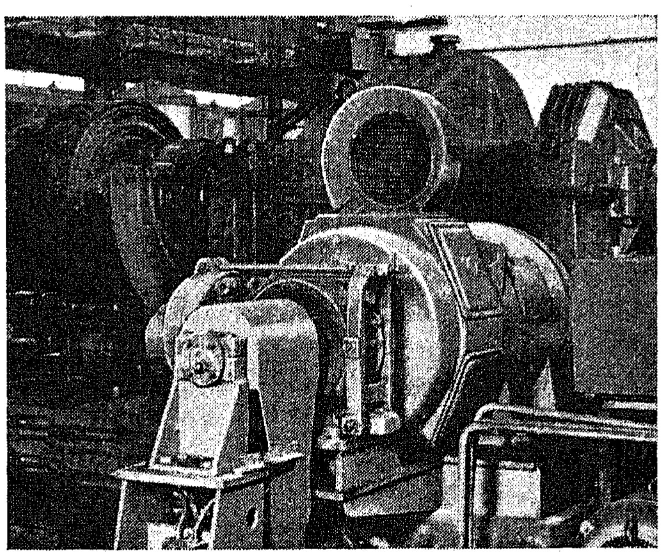

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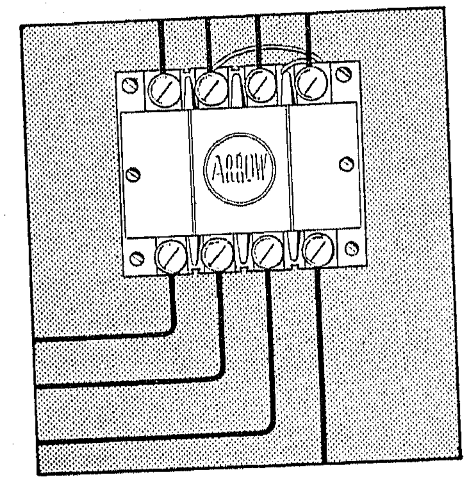

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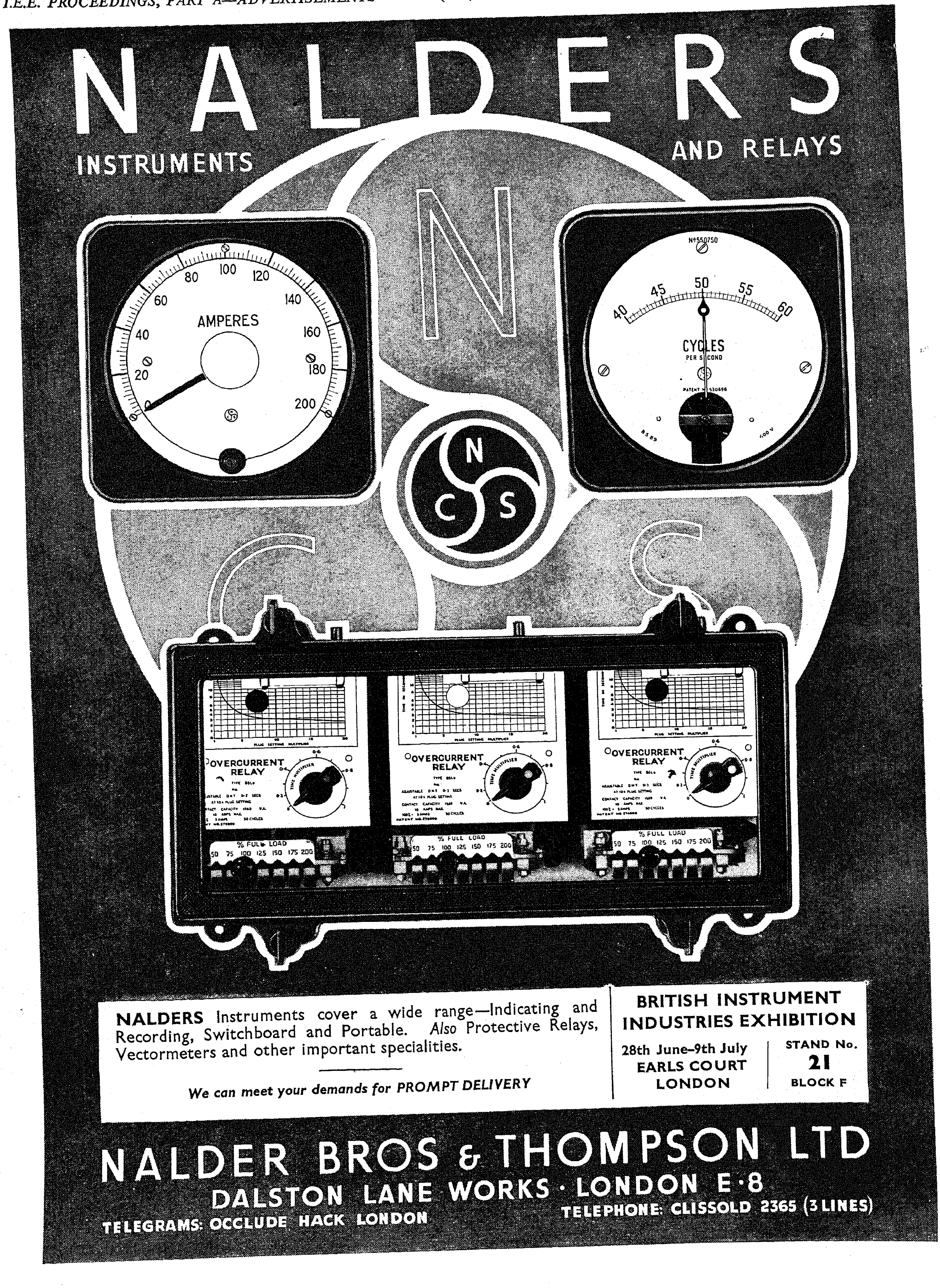

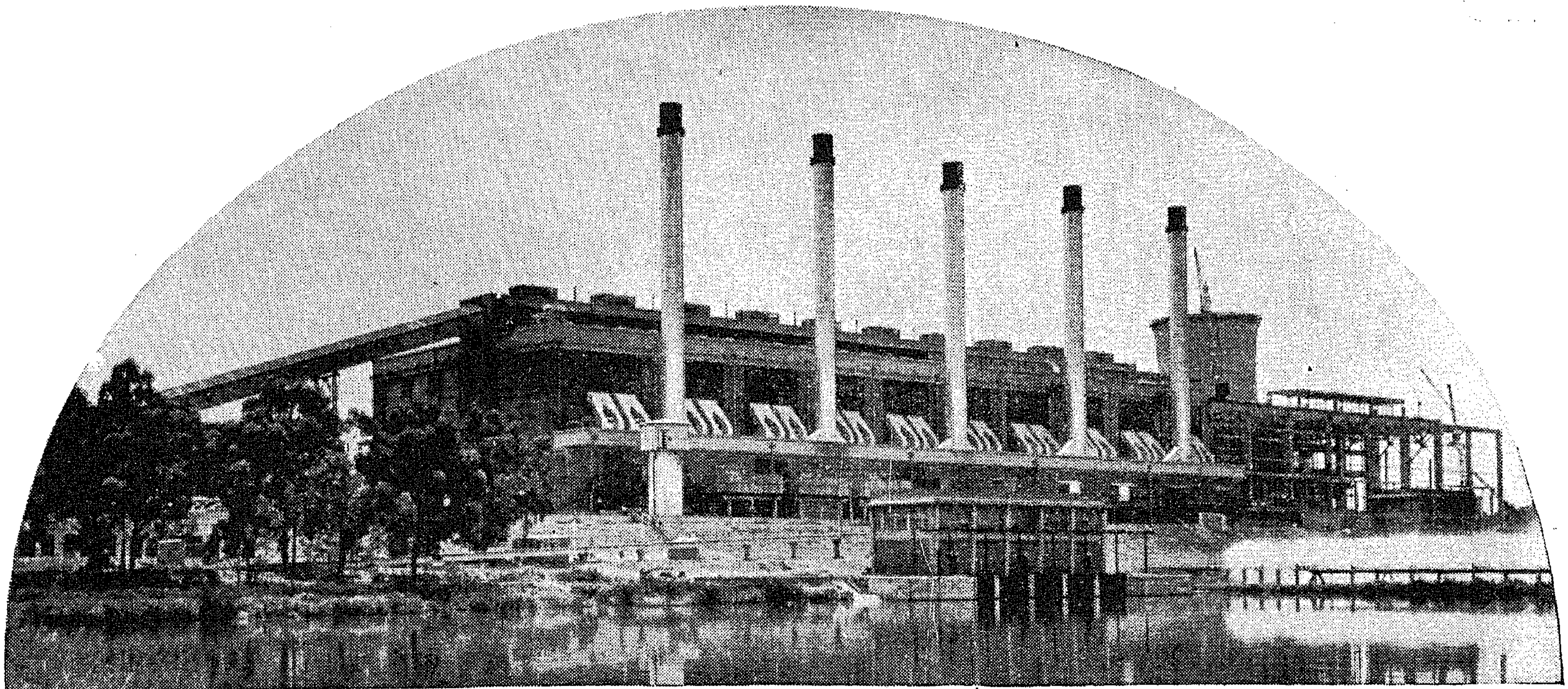

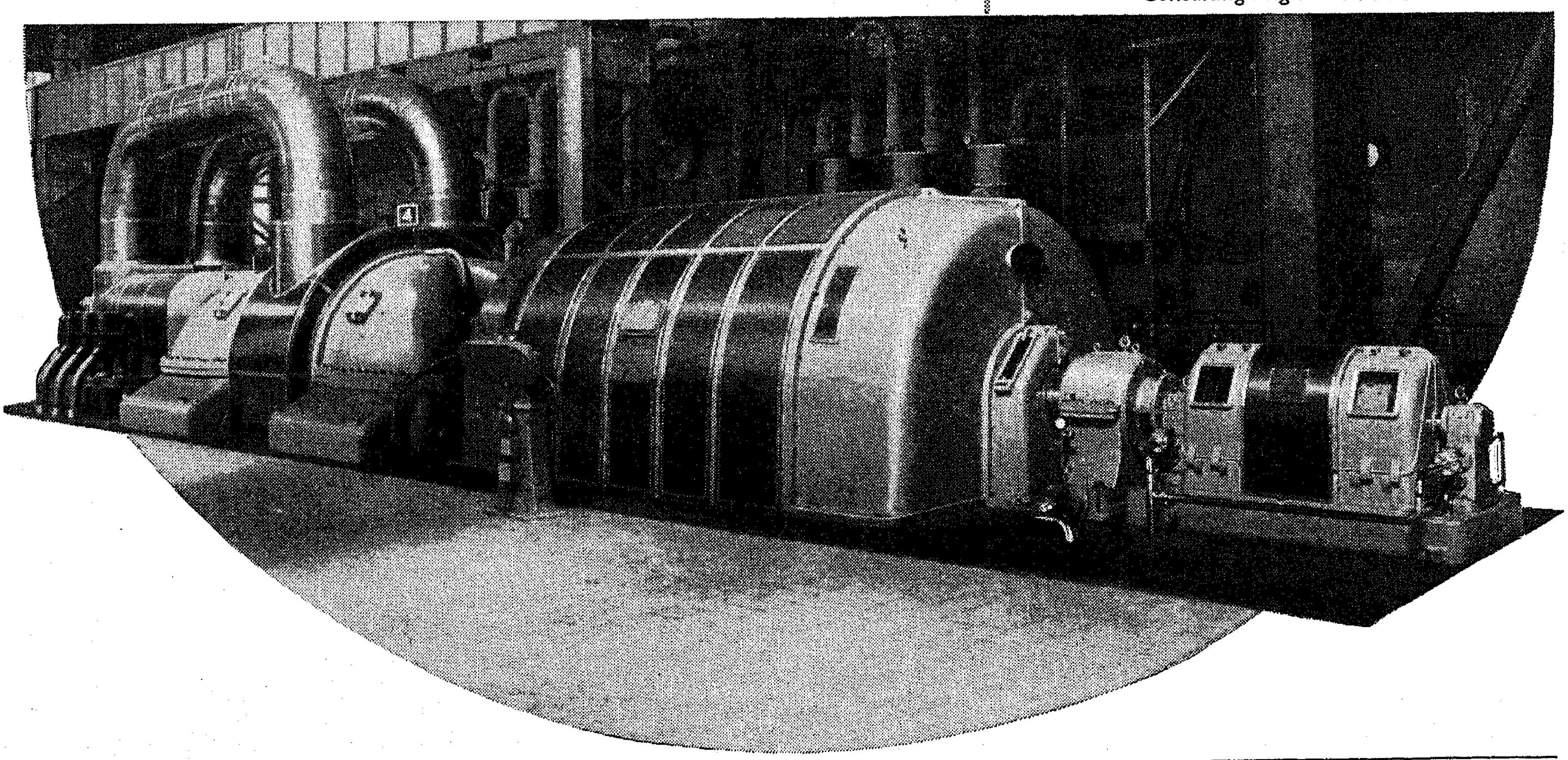

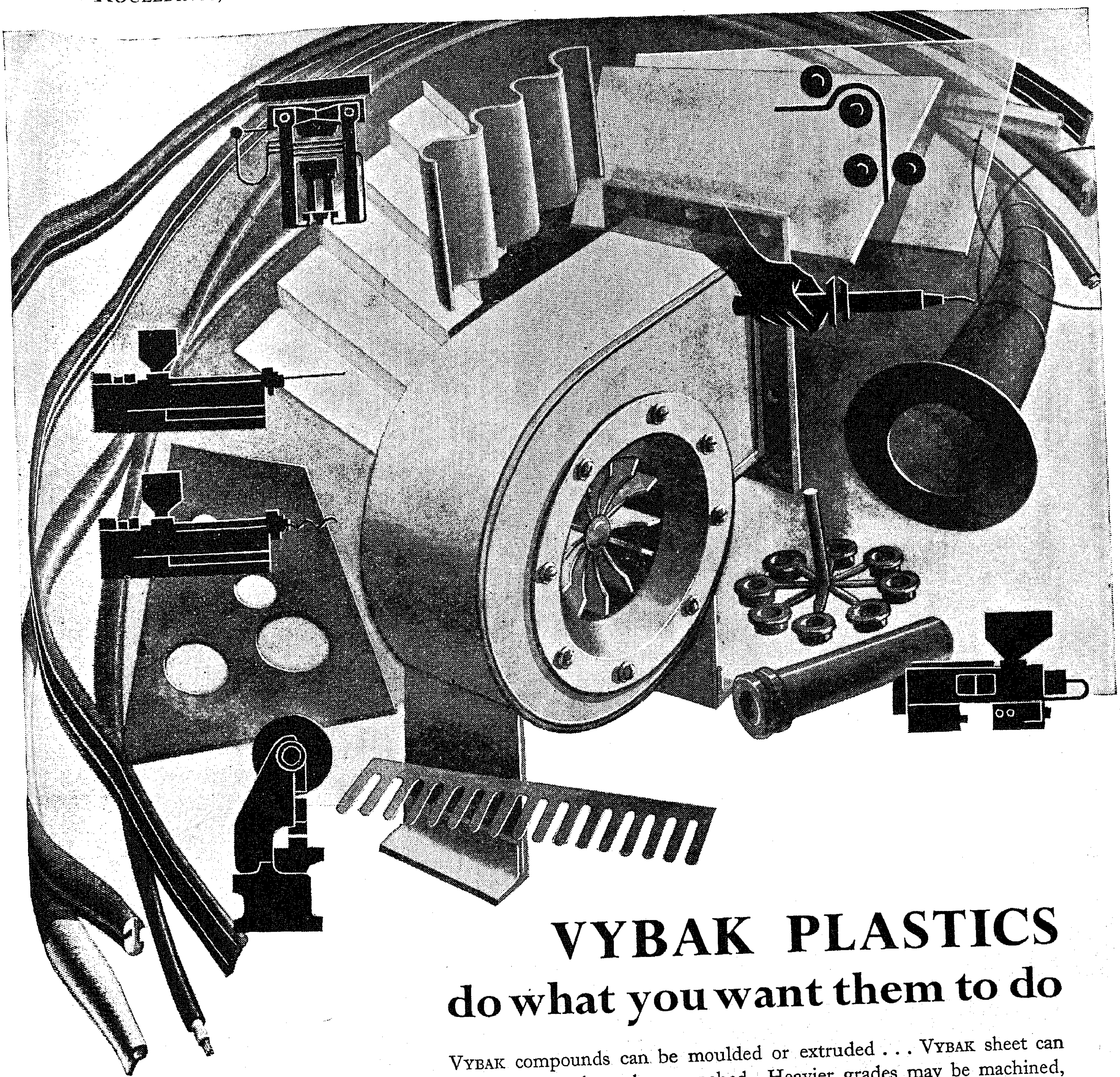

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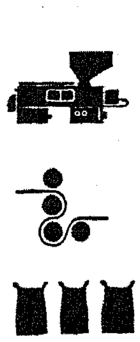

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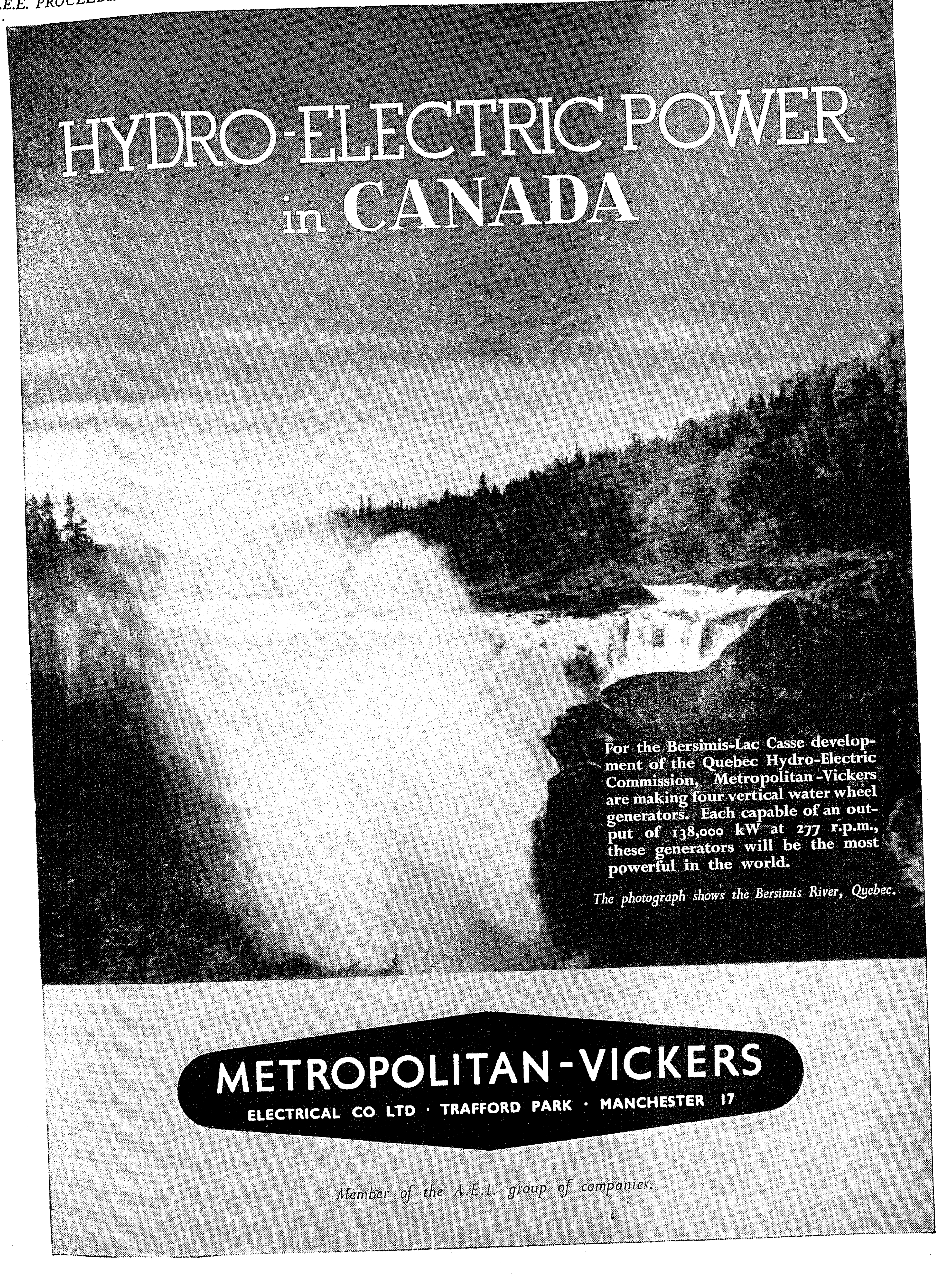
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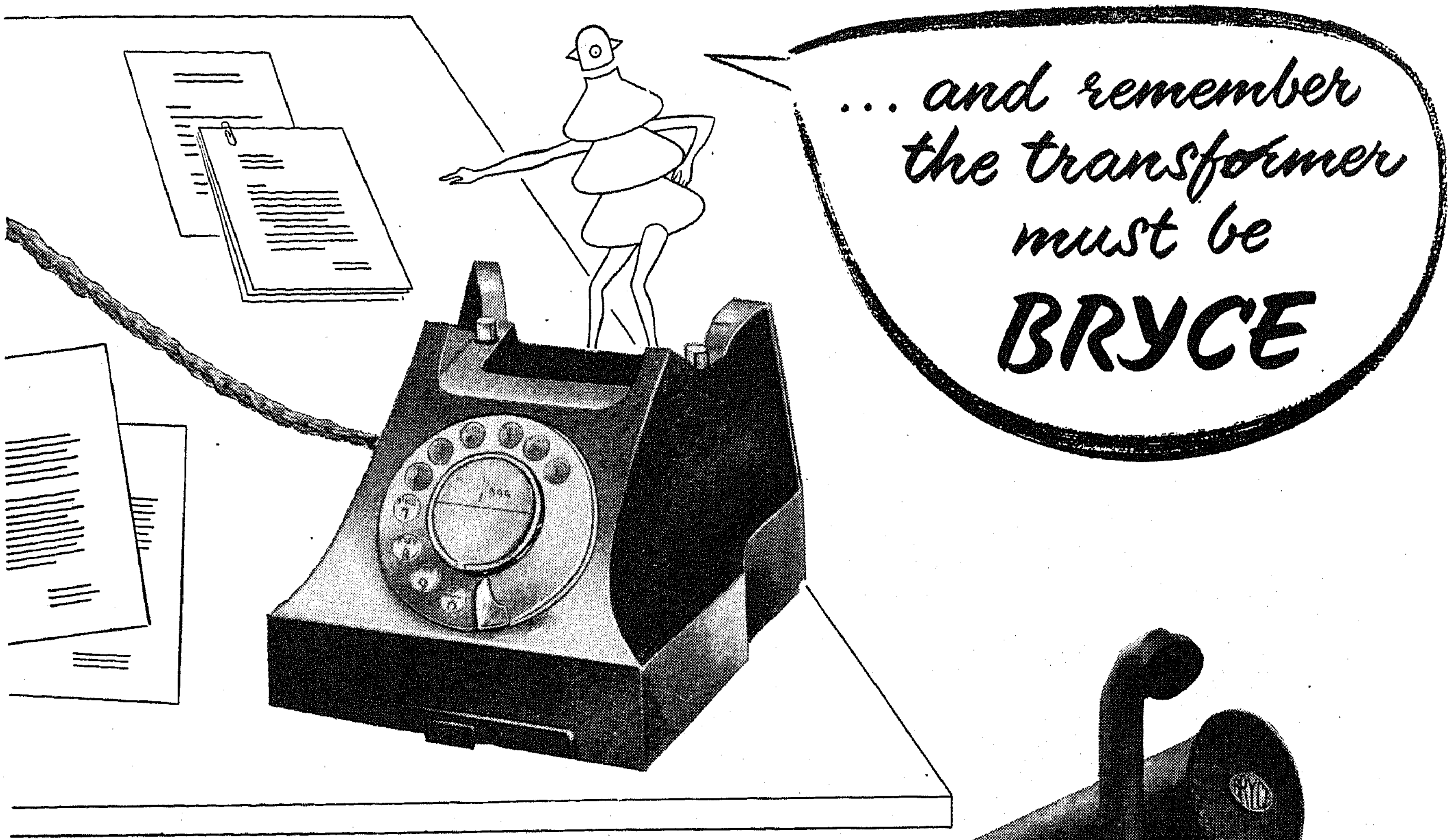
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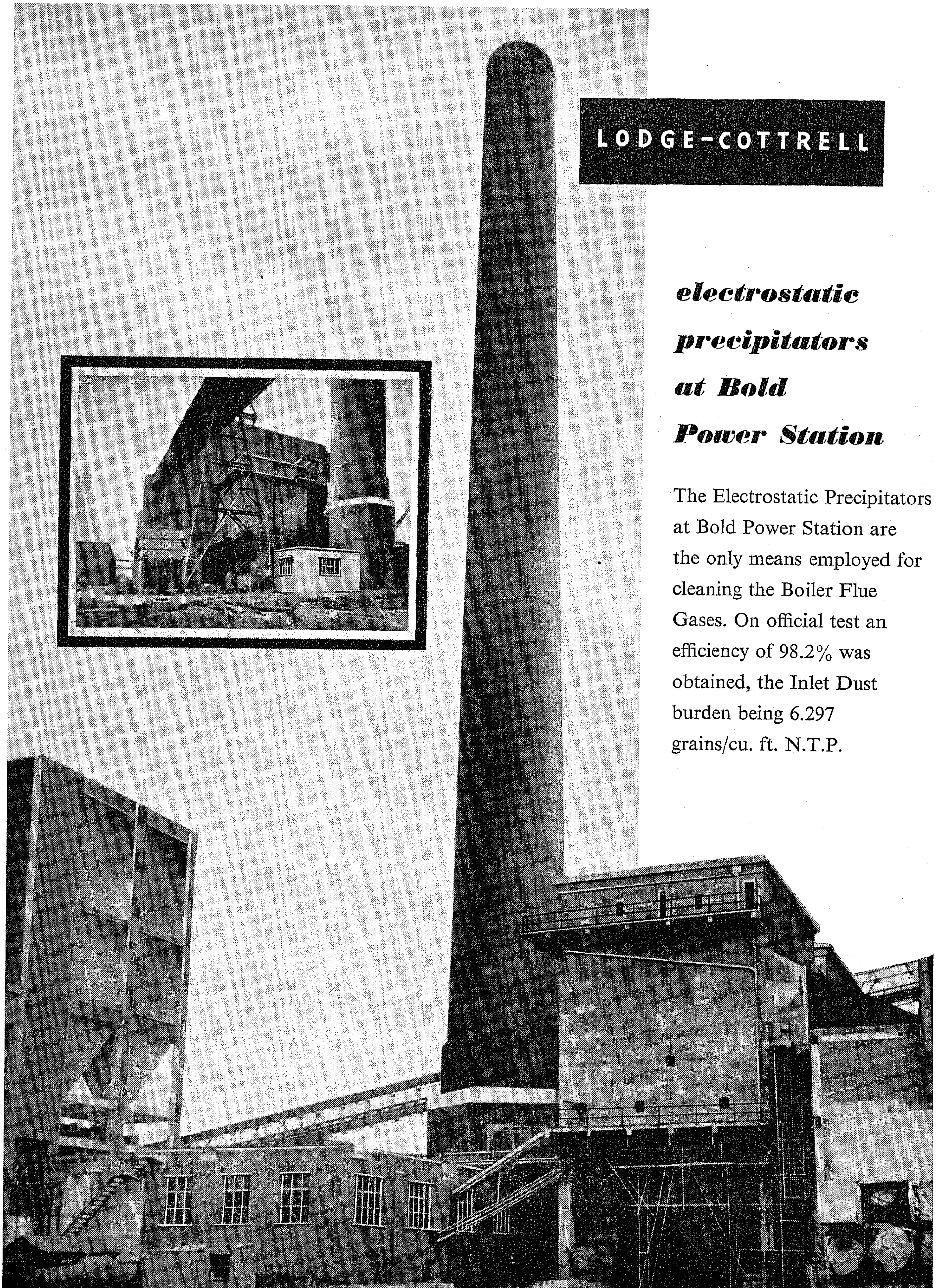

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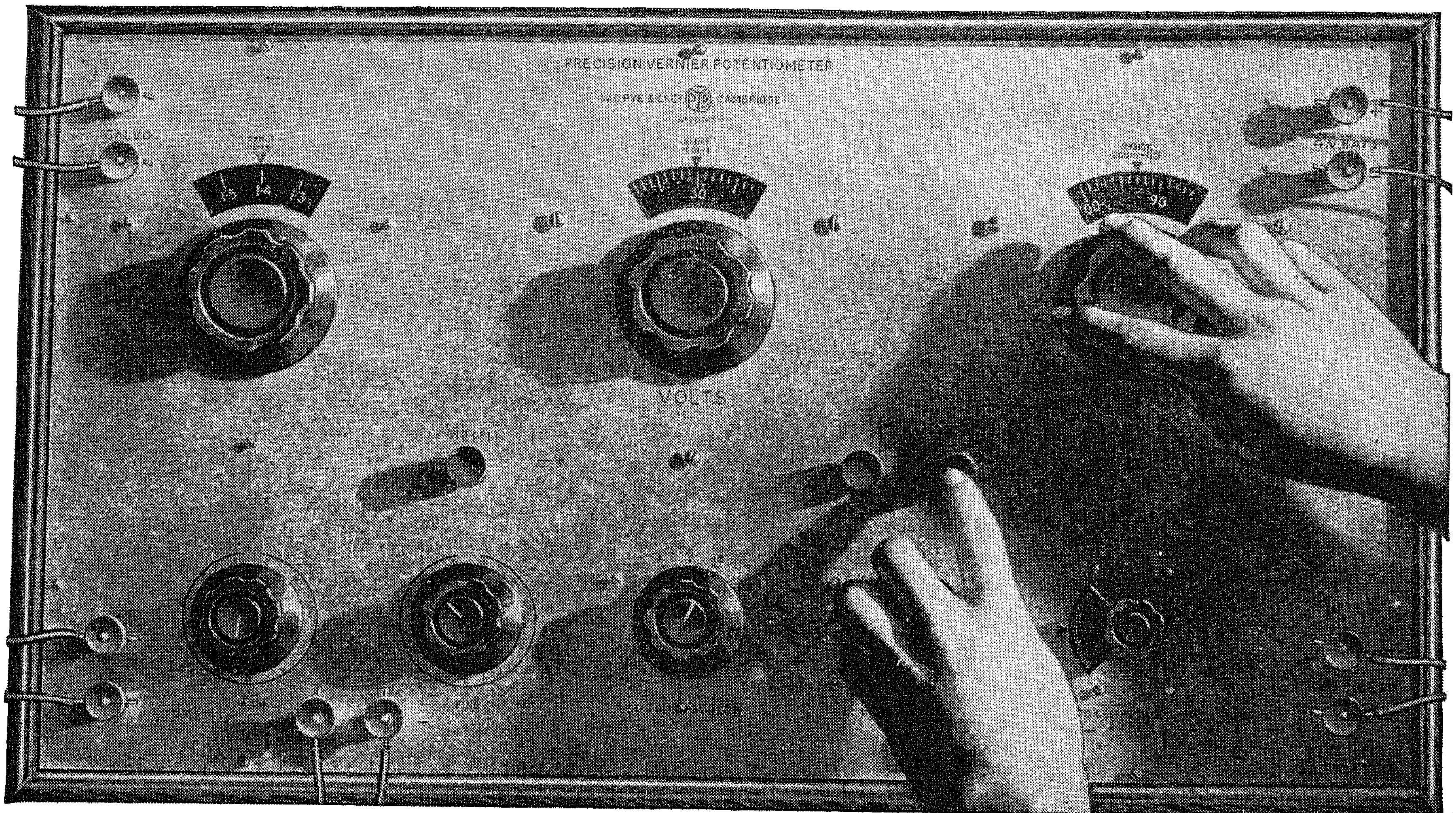

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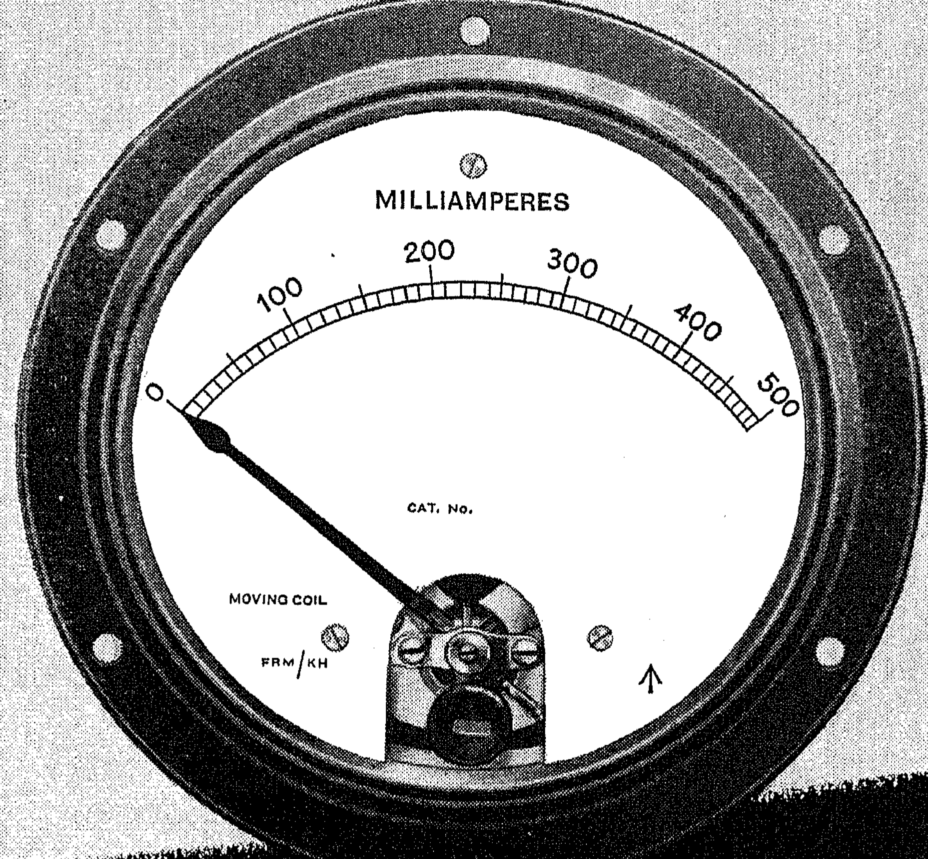
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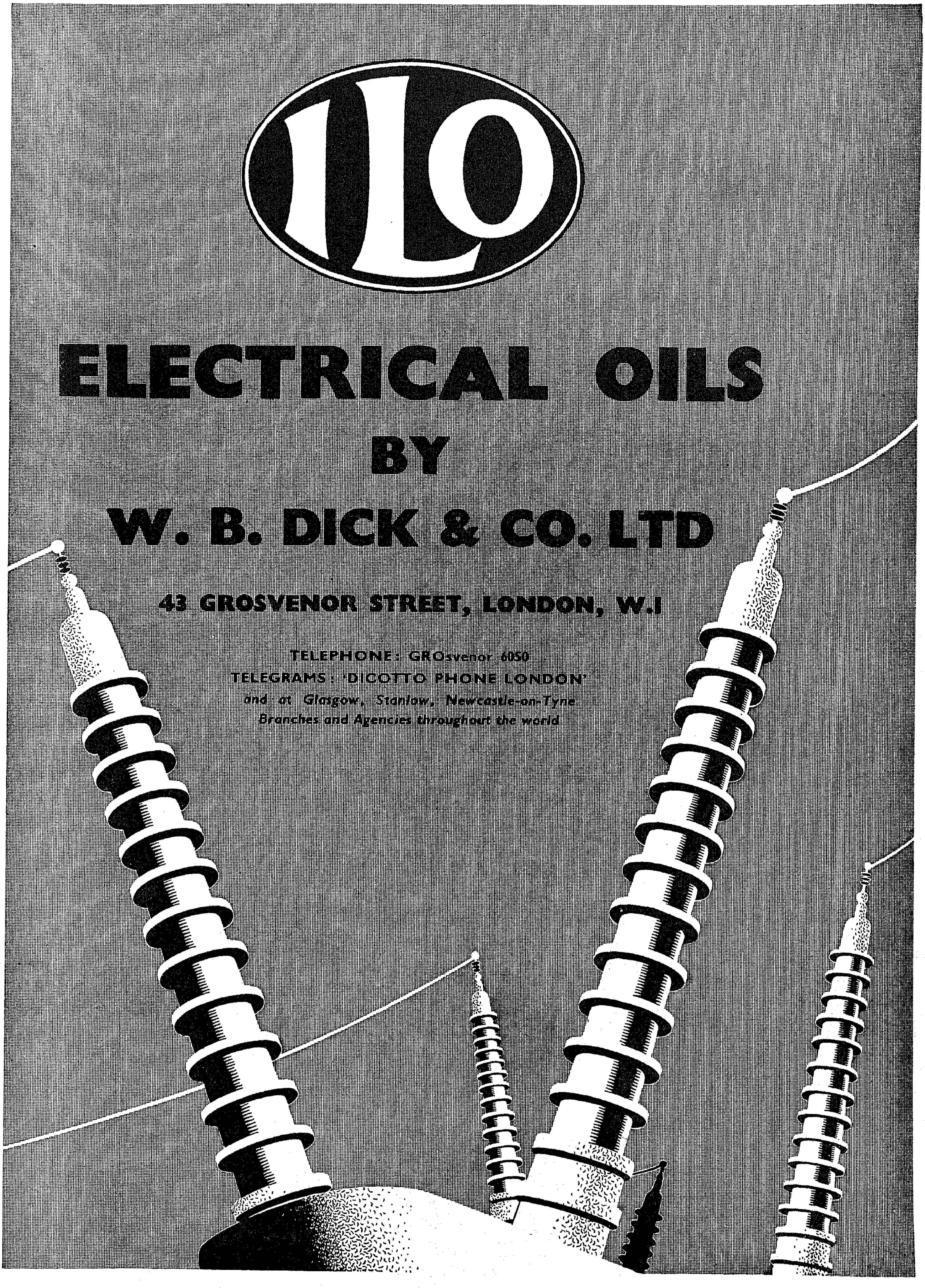
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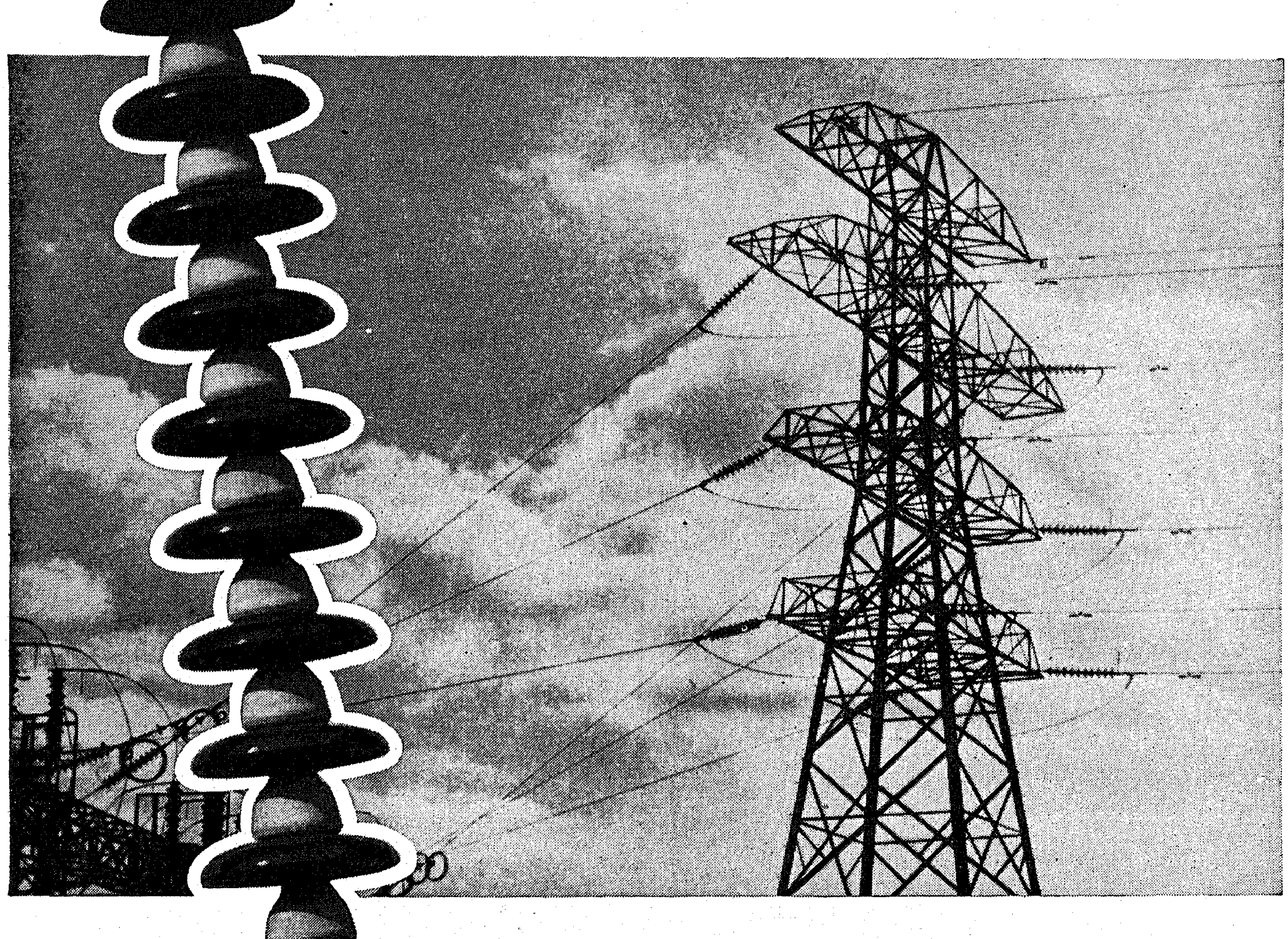

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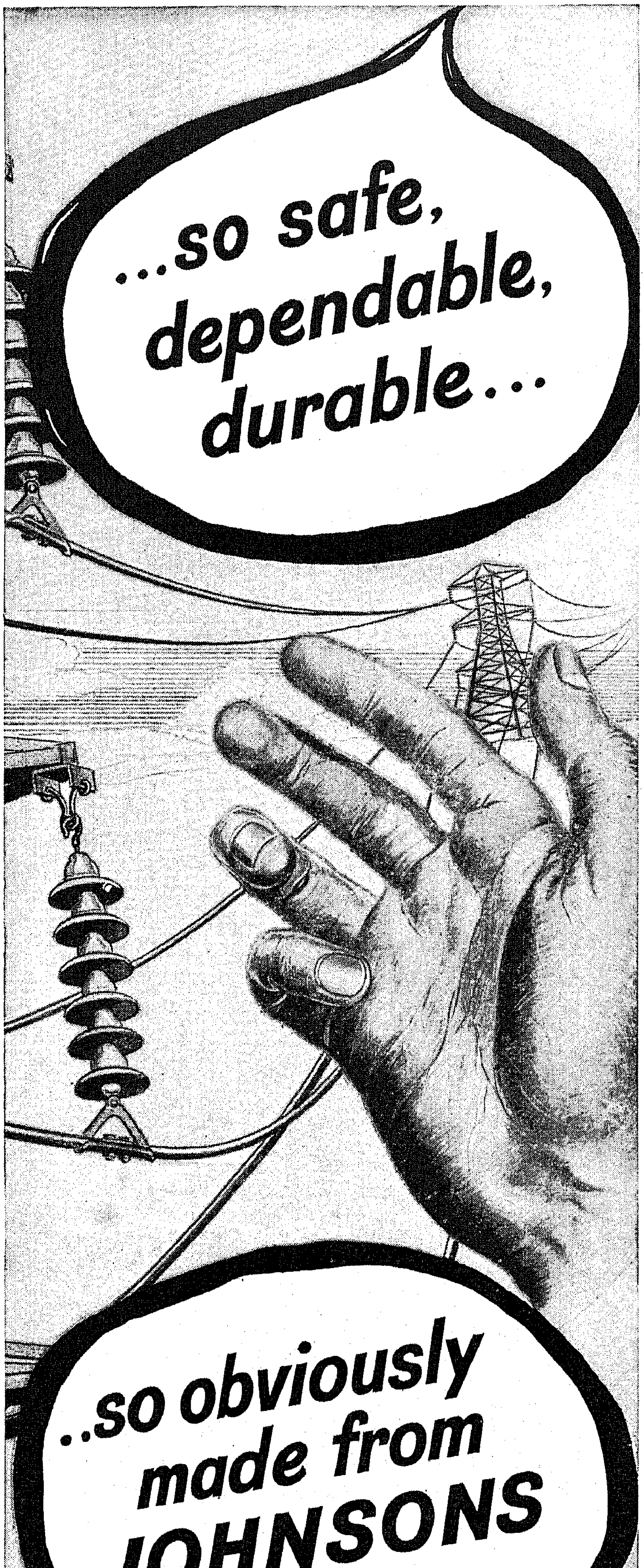

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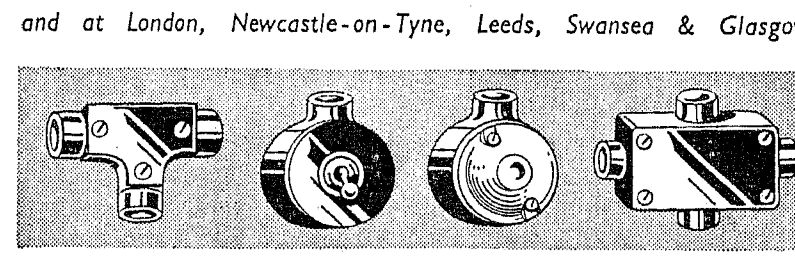

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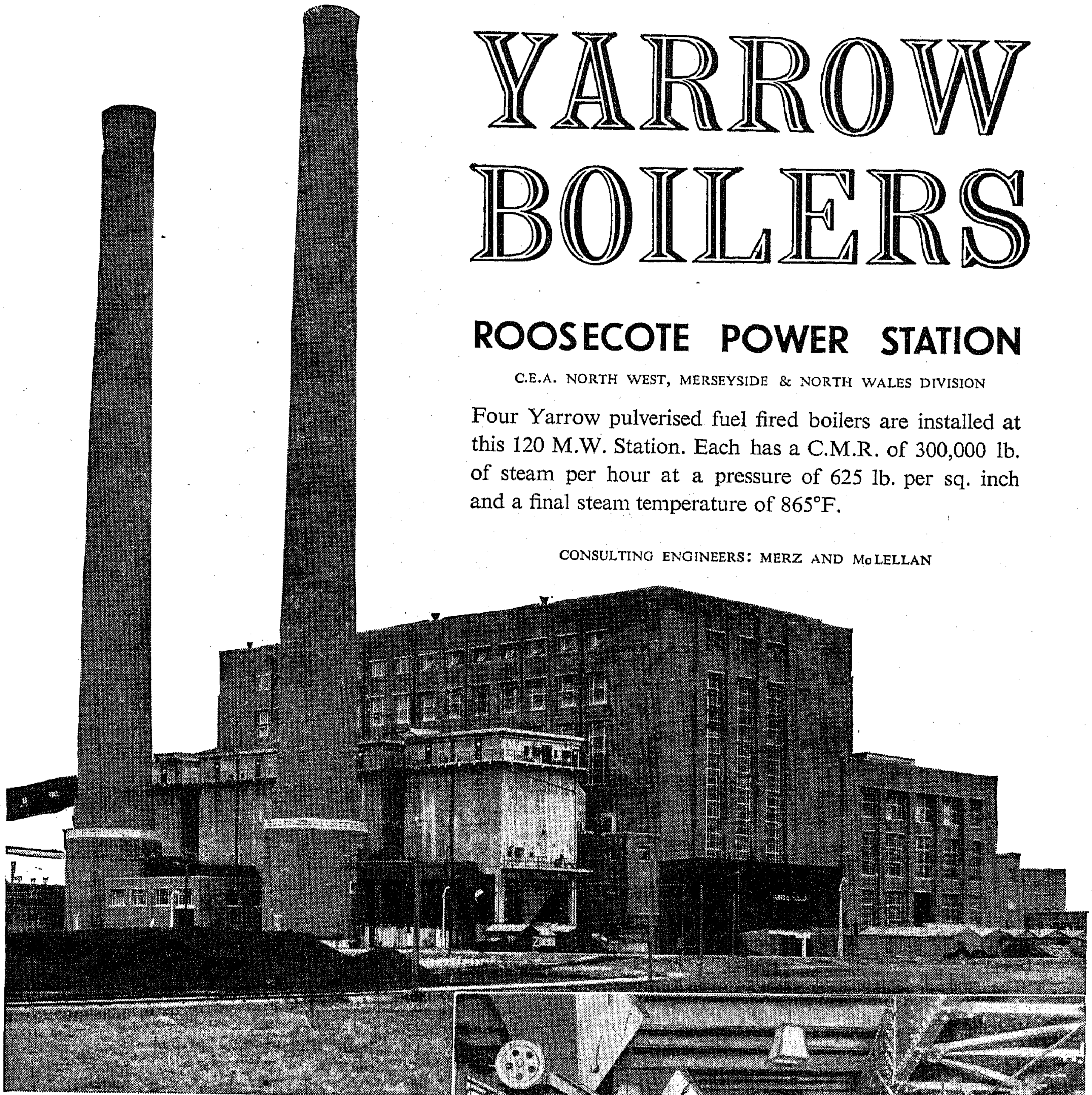

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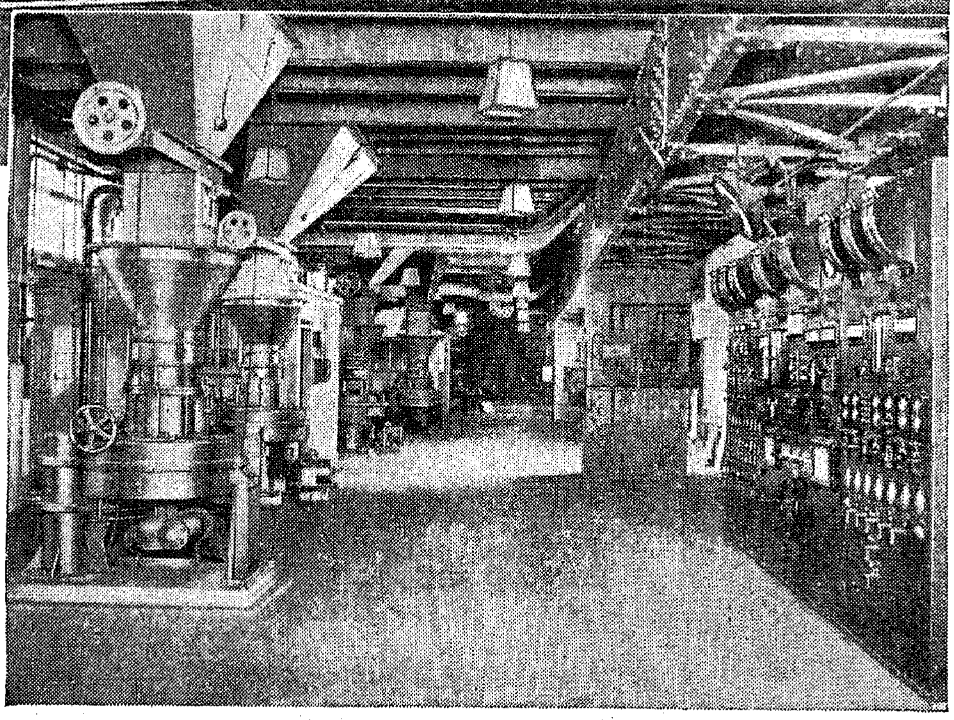

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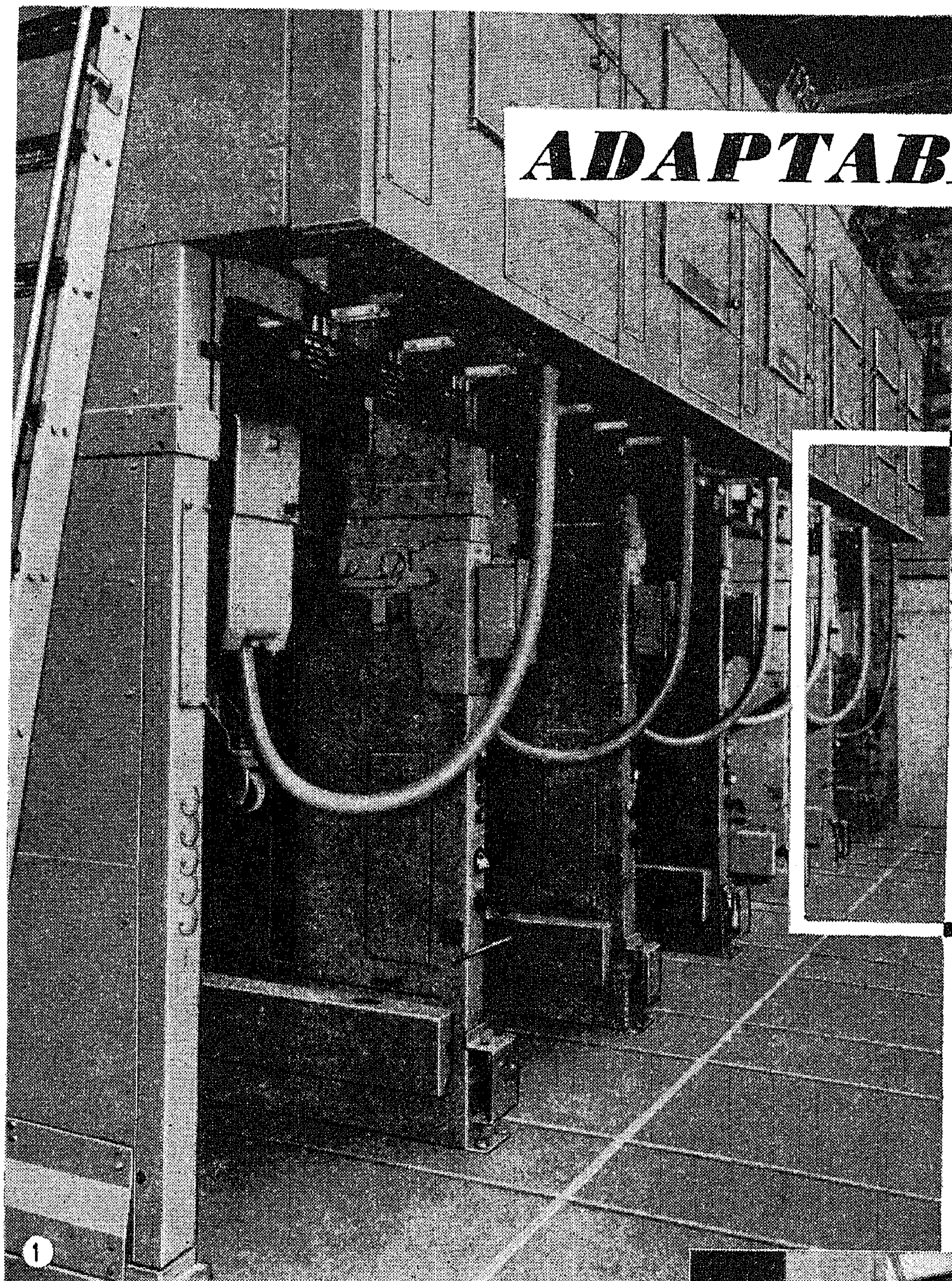

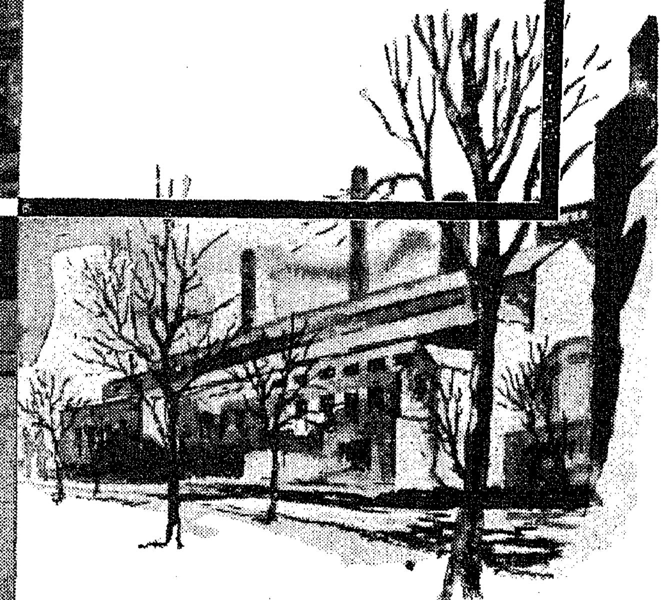

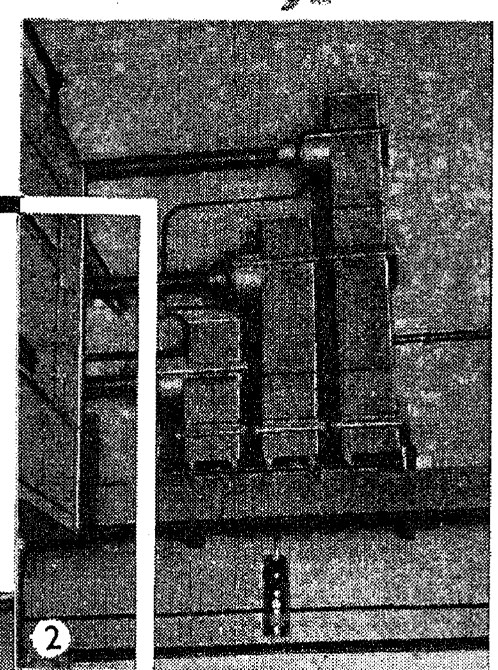

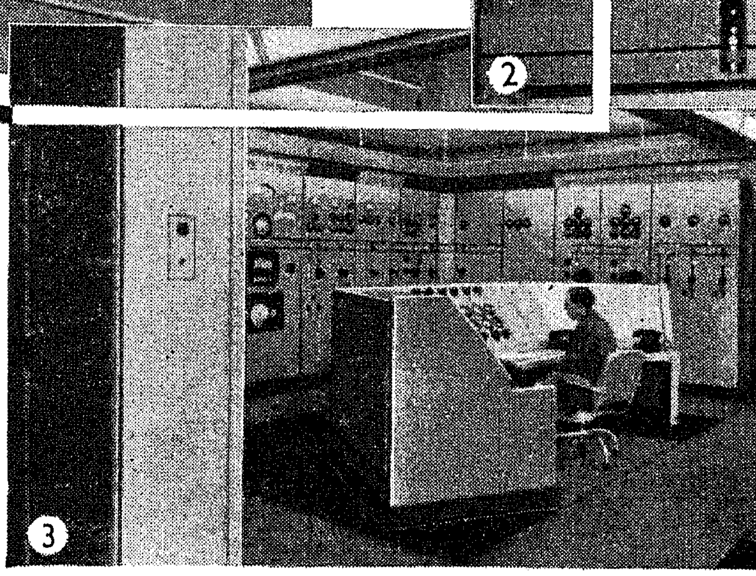

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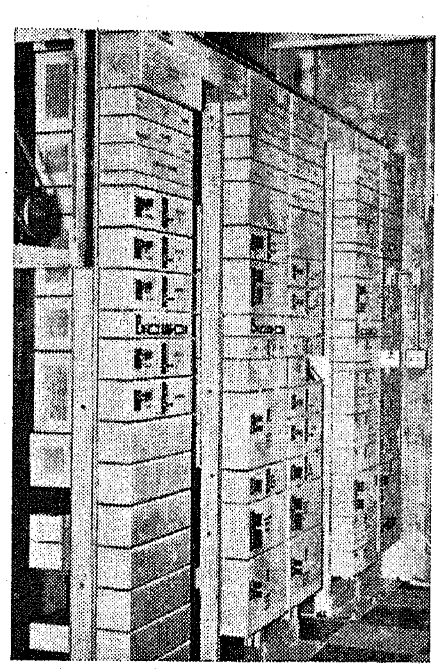

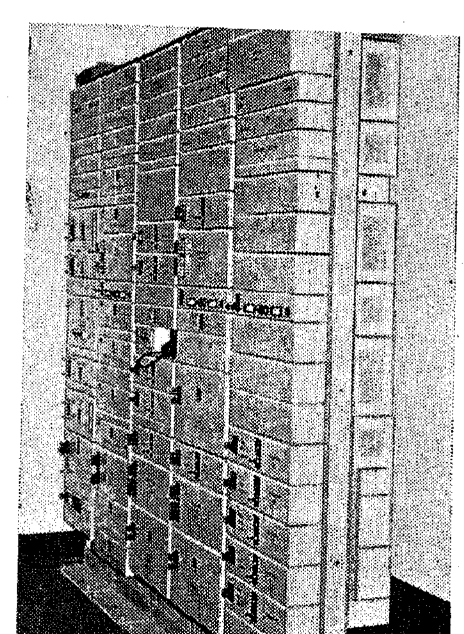

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To receive inquiries from employers seeking the services of qualified professional engineers and to advise such employers, if required, as to the qualifications desirable for the particular vacancy.

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To receive applications for registration for employment from engineers, who by reason of their engineering qualifications are Corporate or Non-Corporate Members of the Institution of Civil Engineers, The Institution of Mechanical Engineers, or The Institution of Electrical Engineers (excluding Associates of The Institution of Civil Engineers); and to charge and receive such registration fees and appointment fees as may from time to time be determined by the Bureau.

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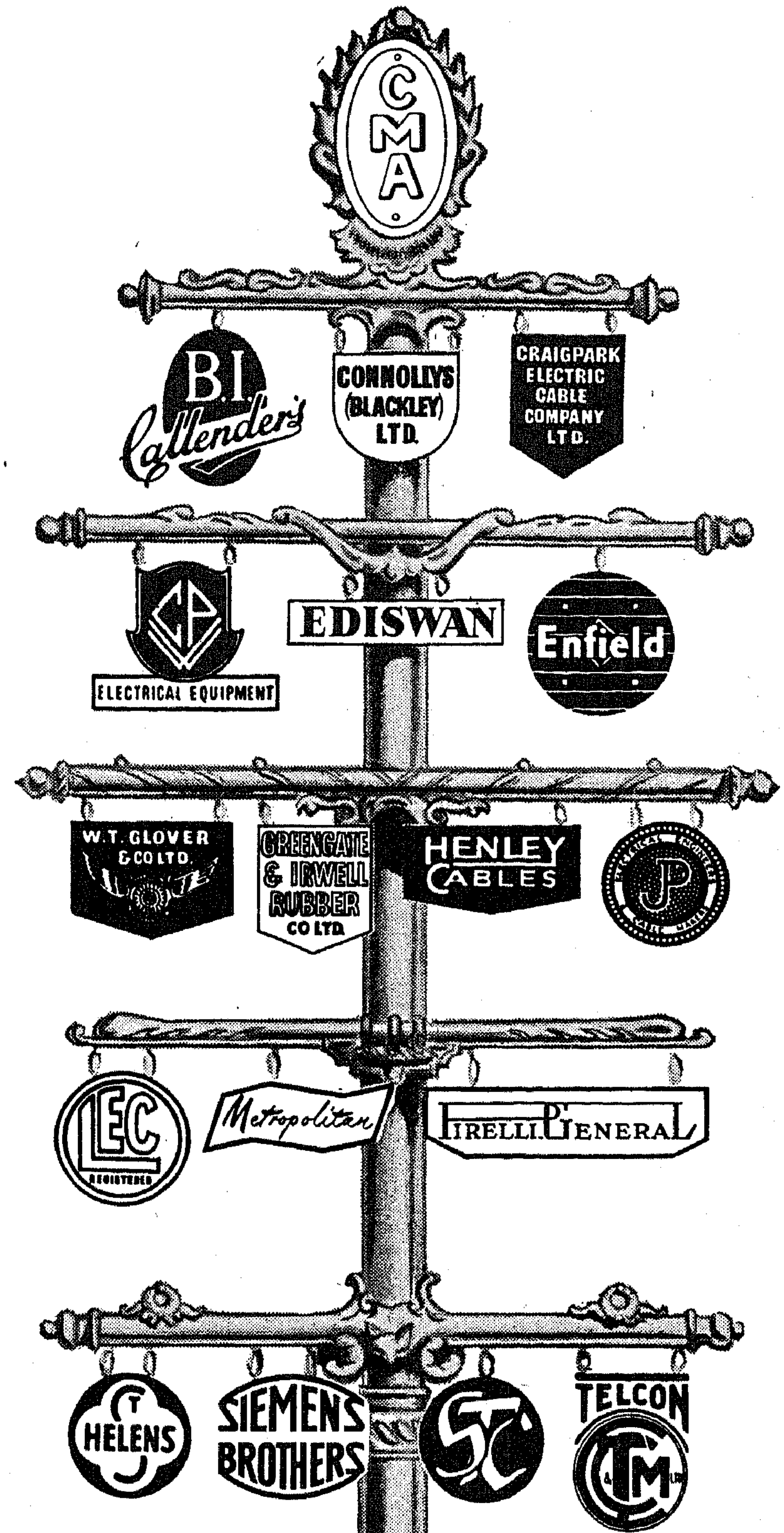

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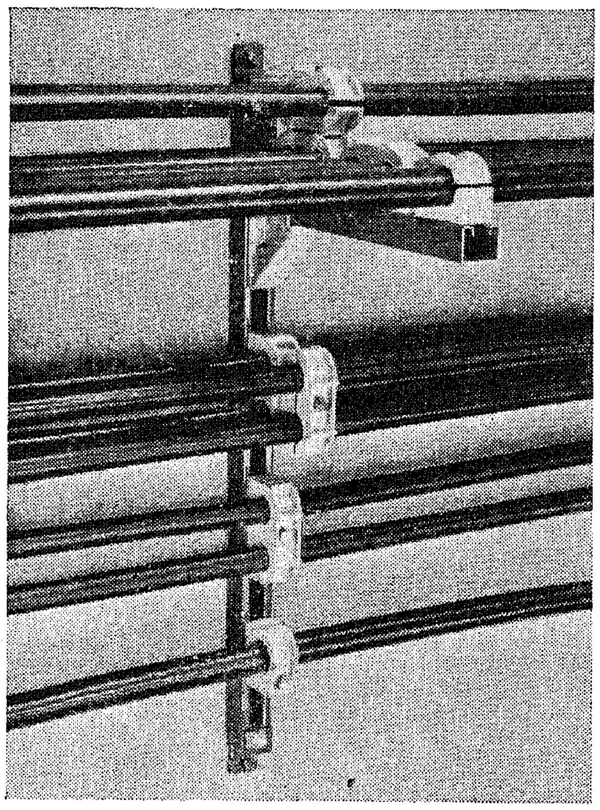

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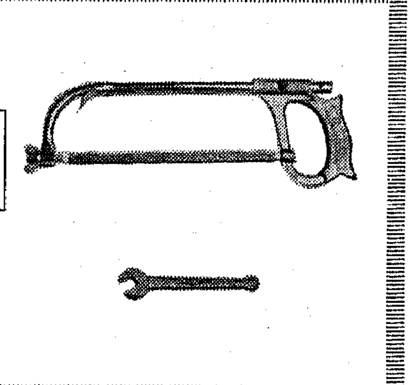

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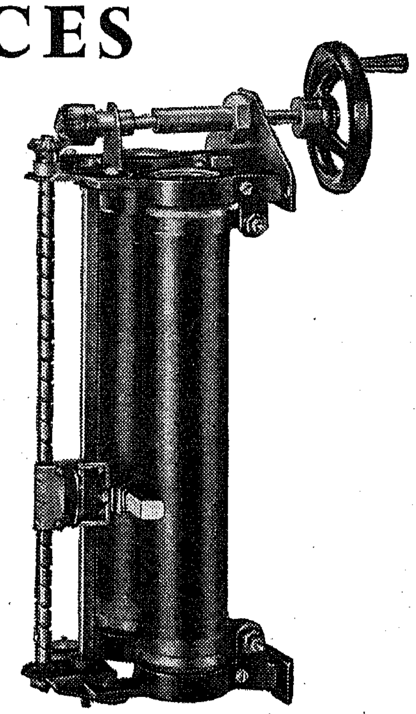

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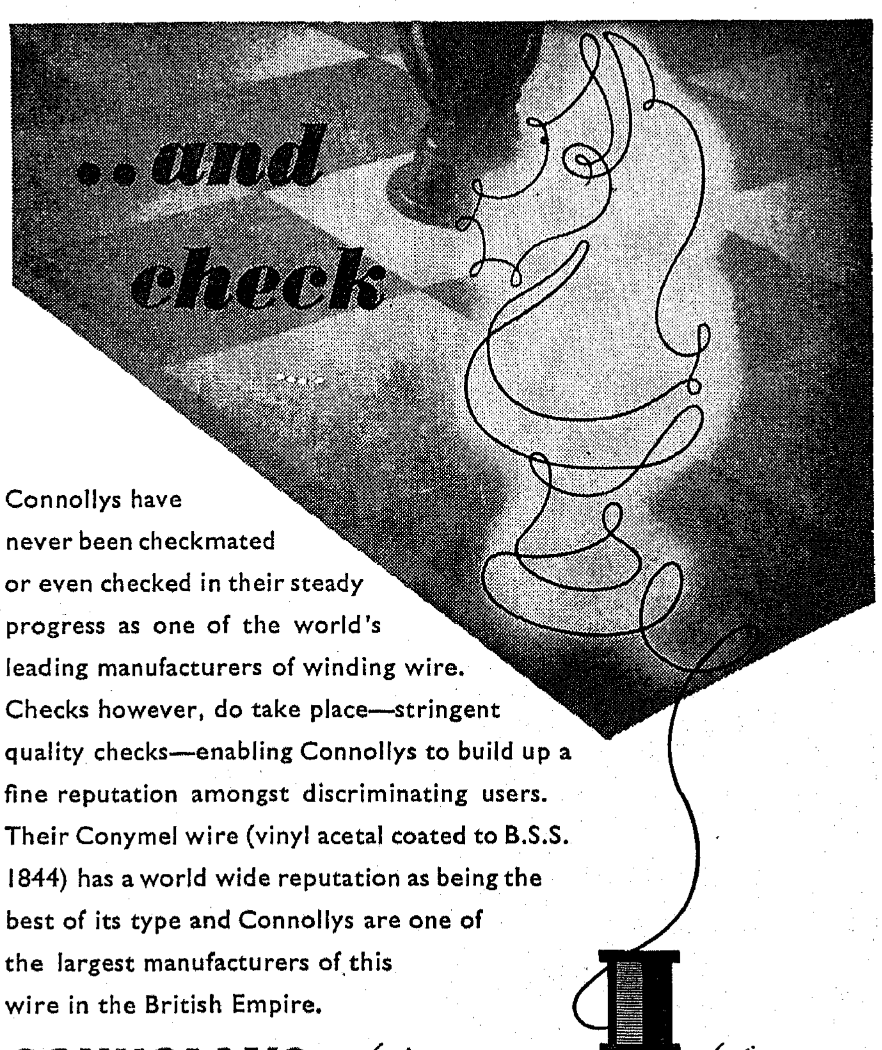

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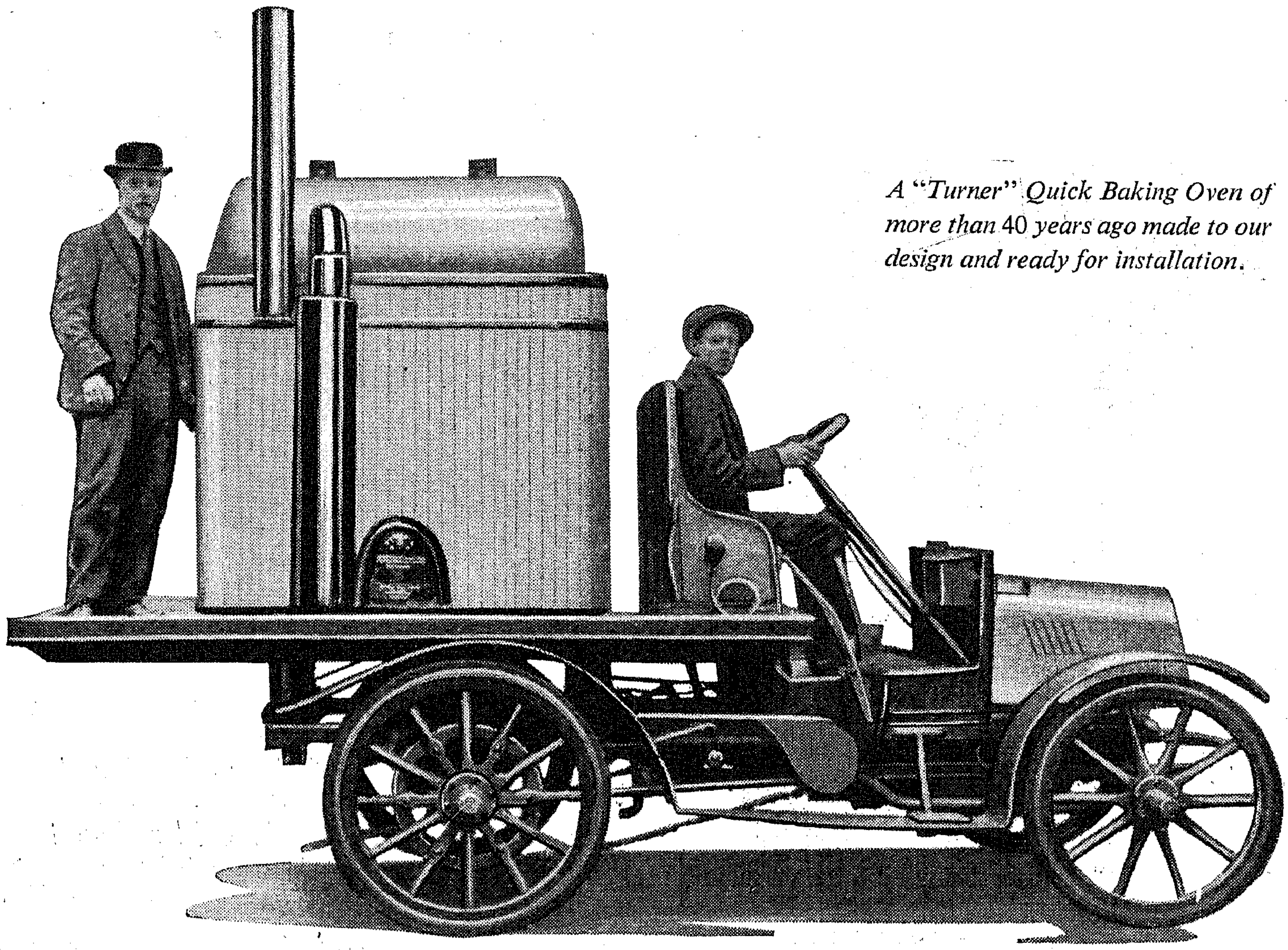

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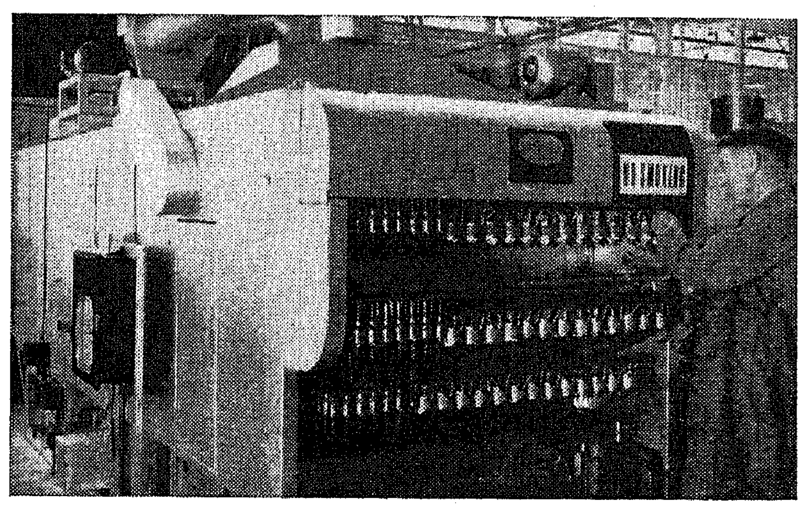

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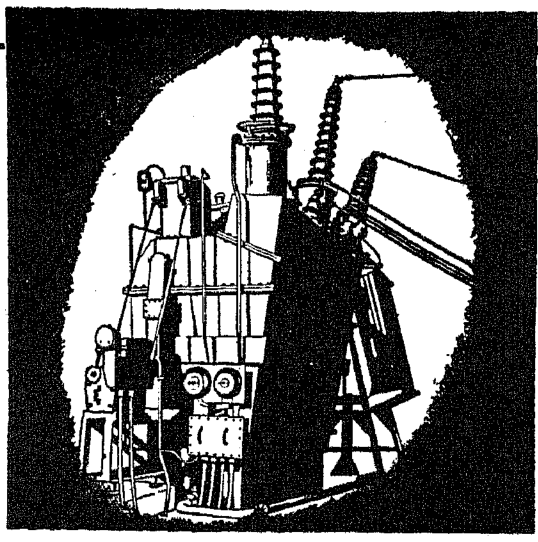

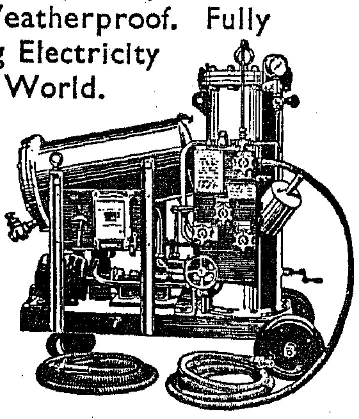

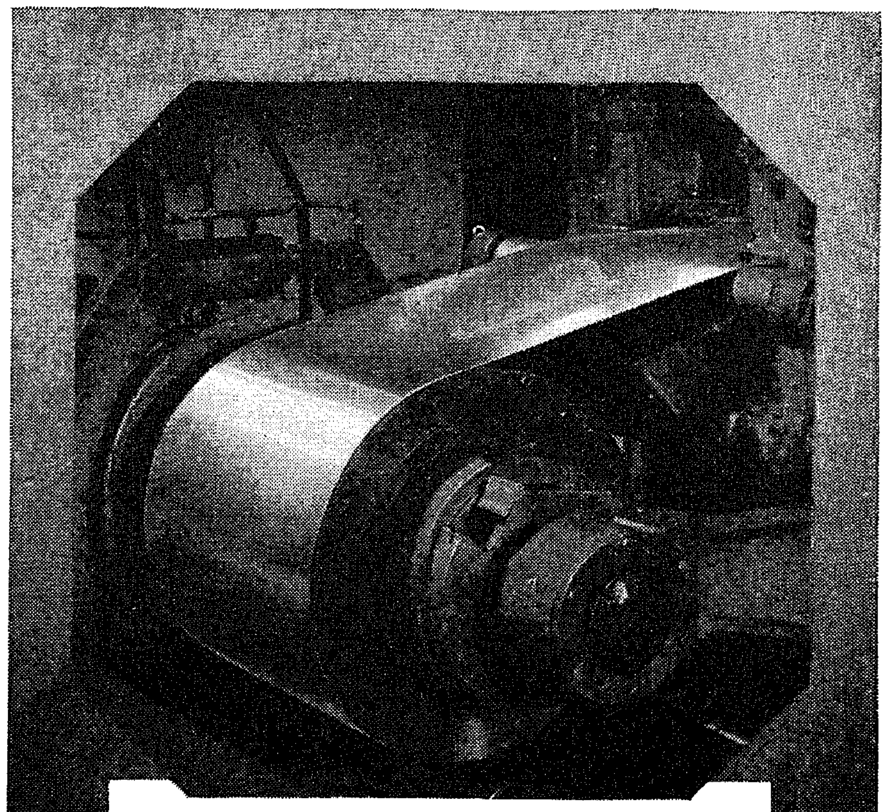

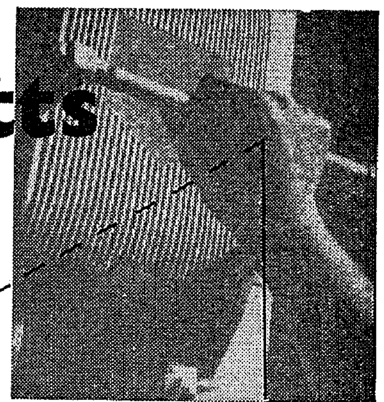

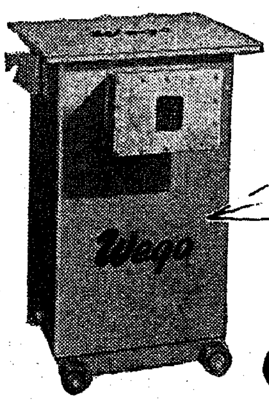
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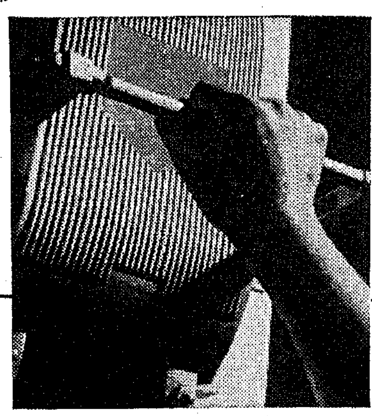

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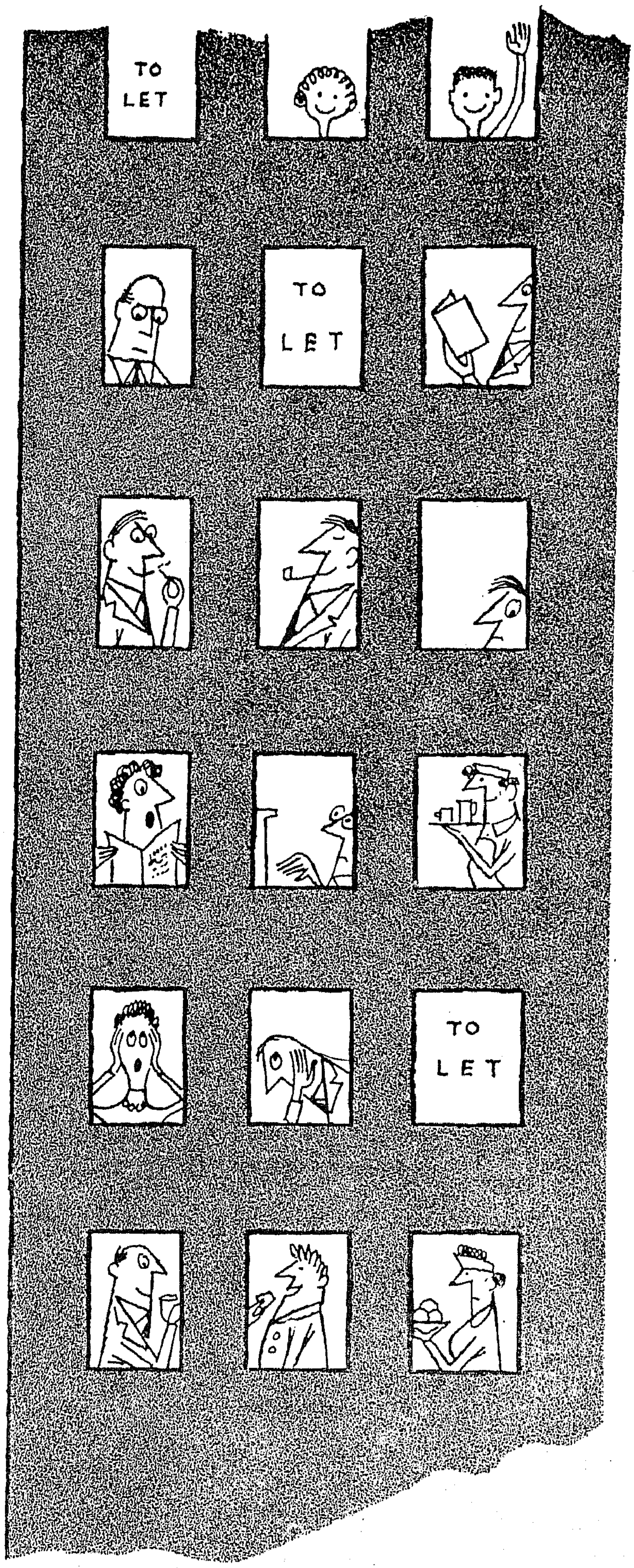

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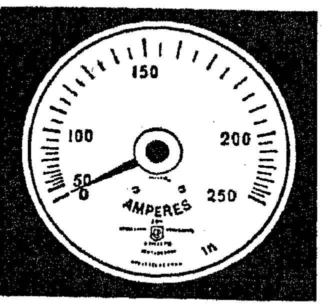

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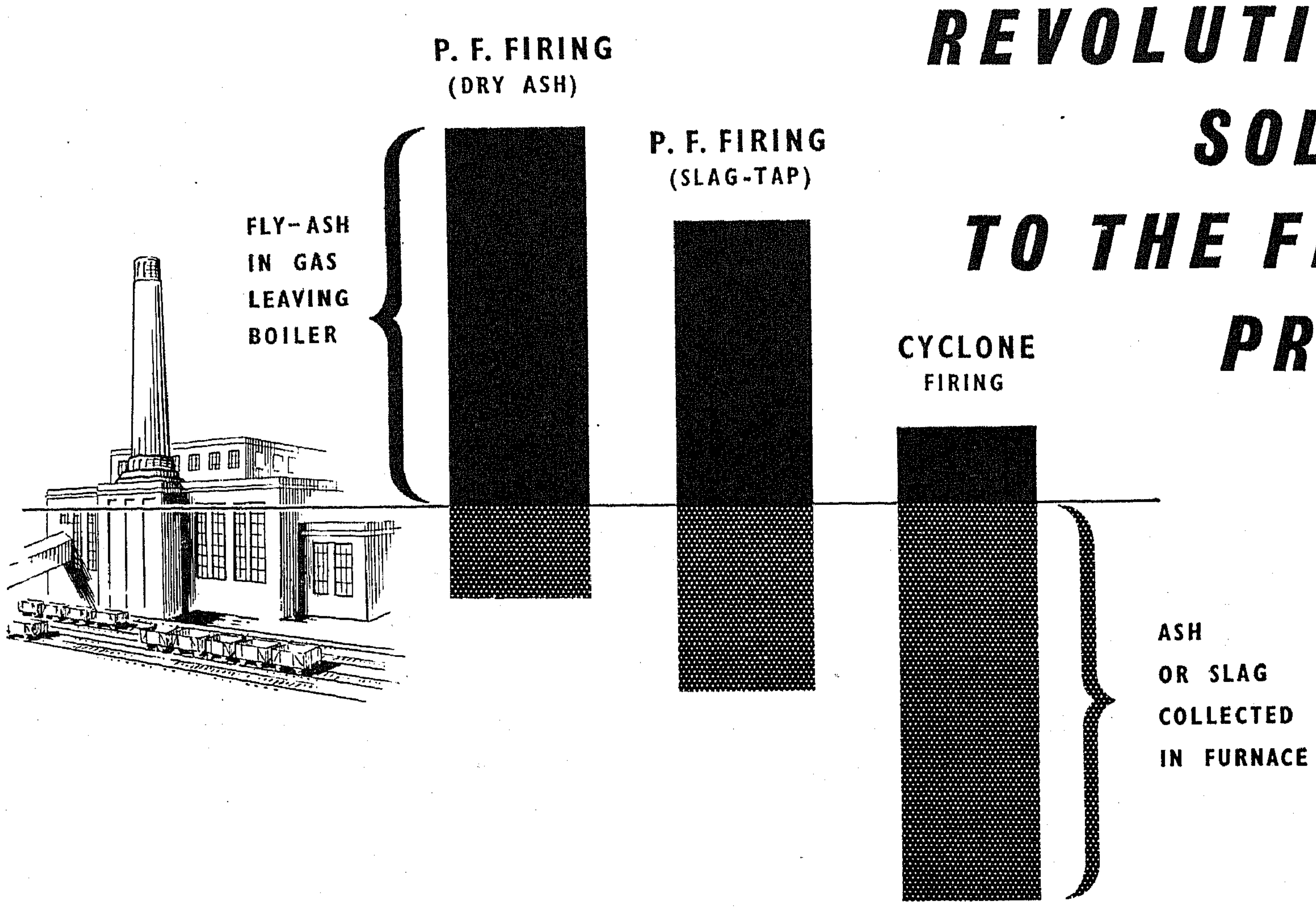

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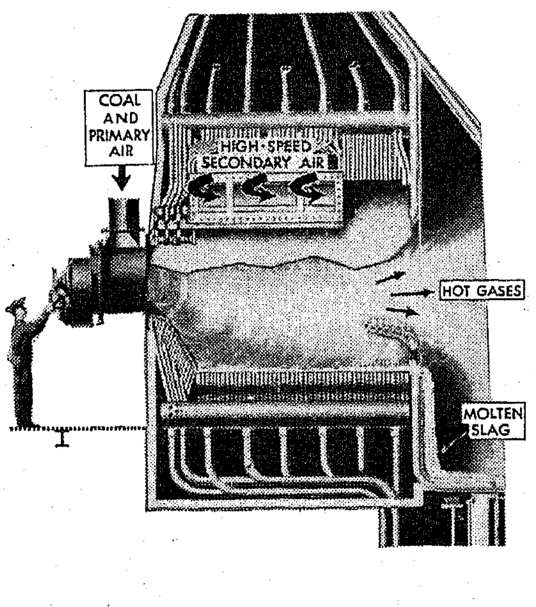

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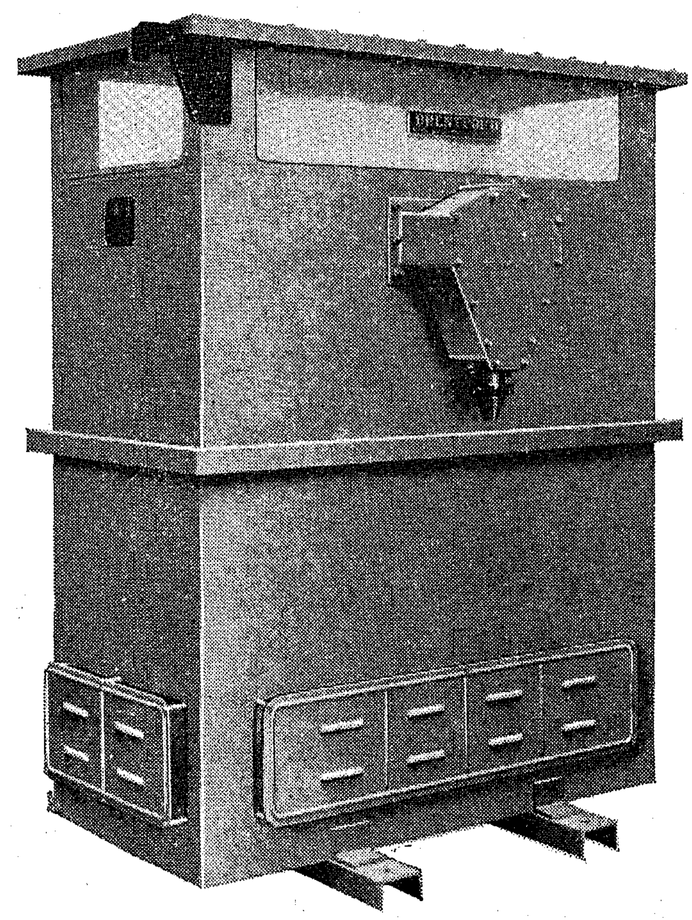

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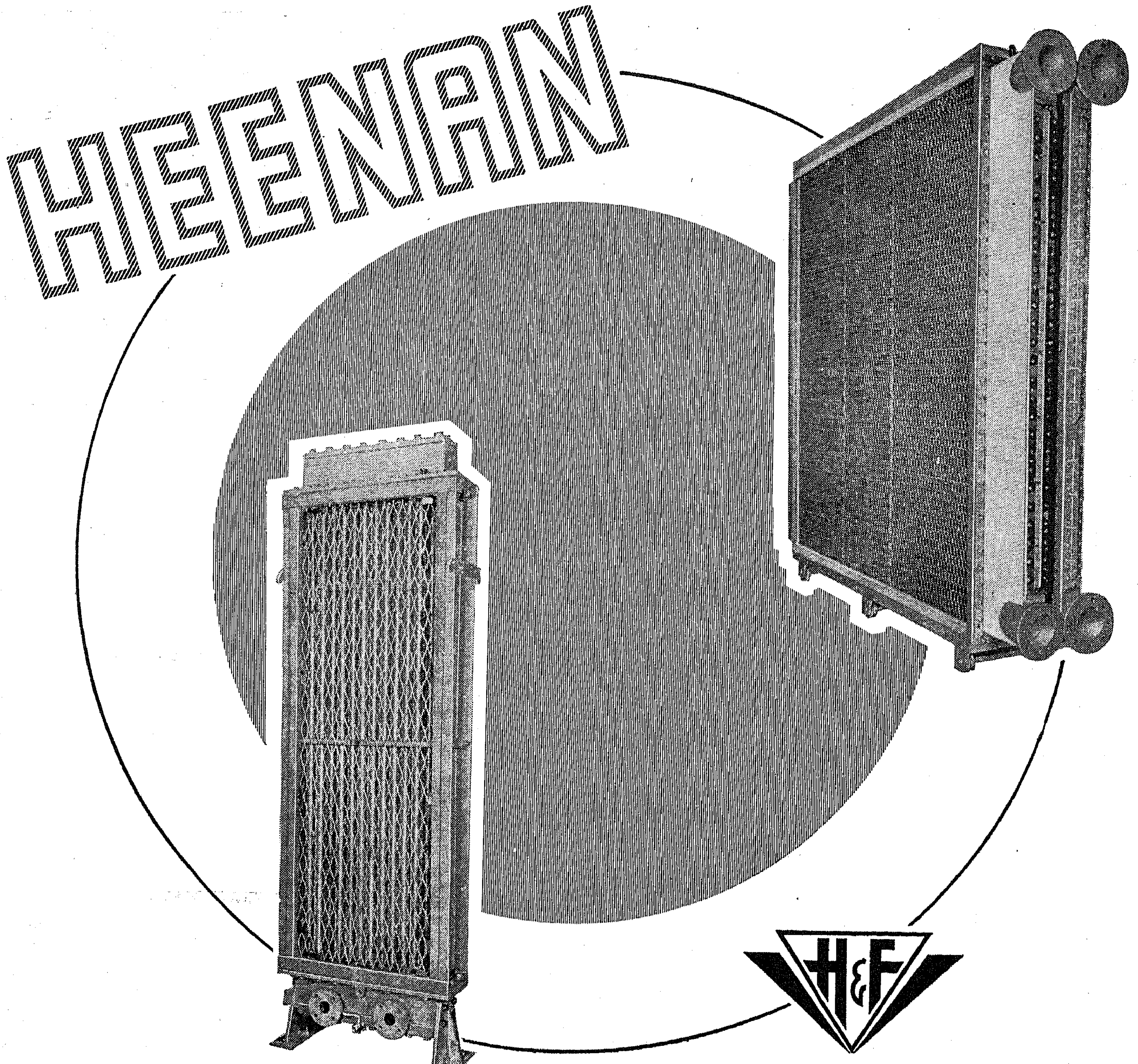
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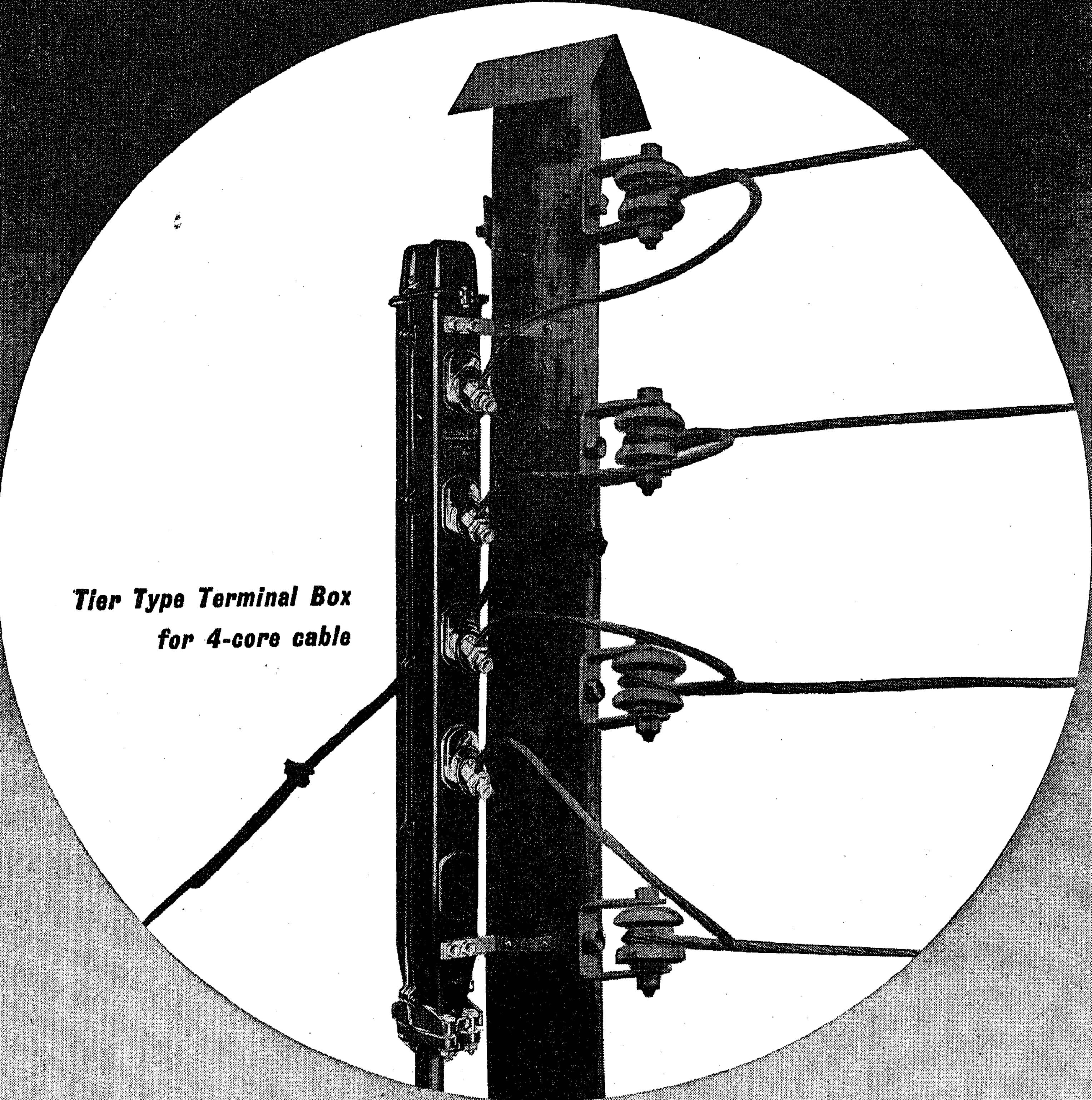

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VOL. 102. PART A. No. 3. JUNE 1955

621.314.212

Paper No. 1674 S
June 1954

SEALED TRANSFORMERS

By E. B. FRANKLIN, Associate.

(*The paper was first received* 15*th December*, 1953, *and in revised form* 15*th March*, 1954. *It was published in June*, 1954, *and was read before the* SUPPLY SECTION 26*th January*, 1955.)

SUMMARY

Sealed transformers have certain advantages, and an outline is given of various sealing methods available.

The internal pressure relations in a particular type of sealed transformer are obtained, taking into account the effect of gas solution in the oil and the chemical reaction of oxygen with the oil.

A review of published experimental work shows how the electric strength of oil varies with gas pressure, and the results are applied to the operating conditions met in sealed transformers. It is shown that special precautions must be taken to avoid large negative pressures.

The paper concludes by showing the derivation of the equations for pressures and estimating the effect of tank-wall deflection on the pressure.

LIST OF PRINCIPAL SYMBOLS

α = Coefficient of volumetric expansion of oil.

k_{ex} = Ratio between the volume of oxygen in the expansion space and the total volume of the expansion space.

k = Solubility factor (i.e. the factor which when multiplied by the partial pressure of gas in pounds per square inch gives the volume of that gas in solution reduced to 760 mm Hg and 0° C per unit oil volume) derived from the Bunsen coefficient.

k_1 = Oil involved in absorbing gas as a fraction of the total amount of oil.

k_2 = Fraction of the gas absorbed by the oil from the expansion space during operation at full temperature remaining in solution when the transformer is cooled.

p_5 = Total gas pressure at oil temperature T_2 and gas temperature T_{a2}.

p_4 = As p_5, but taking into account the solubility of gas in oil.

p_3 = As p_5, but taking into account the solubility of gas in oil and the chemical reaction of oxygen with the oil.

p_s = Sealing pressure at oil temperature T_1 and gas temperature T_{a1}.

p_b = Pressure when cold and when the oil has returned to the saturated state (before oxygen reaction).

p_{b1} = Pressure when cold and when the oil has returned to the saturated state (after oxygen reaction).

p_2 = Total gas pressure when transformer is cooled to temperatures T_{a1} and T_1 and taking account of the solubility of gas in oil.

p_1 = As p_2, but taking additional account of the chemical reaction of oxygen with the oil.

p_g = Total pressure of gas in solution in the oil (when sealed).

T_2 = Average oil temperature in the main tank when the transformer is loaded.

T_1 = Average oil temperature in the main tank when the transformer is sealed.

T_{a2} = Gas temperature in the expansion space when the transformer is loaded.

T_{a1} = Gas temperature in the expansion space when the transformer is sealed.

T_v = Average temperature of oil in the expansion vessel.

v_e = Volume of expansion space.

v_0 = Total oil volume.

v_g = Volume of gas in solution in the oil (reduced to 760 mm Hg and 0° C) per unit oil volume at partial pressure of p lb/in^2.

$y = v_e/v_0$.

y_1 = Distance of extreme fibres in tank wall from axis of bending.

(1) INTRODUCTION

The subject of the paper is of general interest to transformer manufacturers and users at the present time, with the object of attaining a higher degree of oil preservation than is provided by the well-known oil conservator. The Midlands Electricity Board are operating a number of sealed transformers on an experimental basis, whilst their use in one form or another is almost universal in America. Électricité de France are now considering sealed transformers for distribution purposes.

Experiment shows that the pressures occurring in sealed transformers do not agree with those calculated from simple relations of volume and temperature, and it was concluded that the discrepancy is due partly to the gas in the expansion space passing into solution in the oil and partly to the disappearance of some of the gas by chemical reaction with the oil.

If the gas pressure could be calculated with reasonable accuracy it would be industrially important, because of the need for design data; moreover, if the pressure and temperature relations are known, the presence of leaks may be ascertained; again, pressure is known to affect the breakdown strength of the oil, and if this variation in strength is to be known it is obviously necessary to know the pressures as well as the other factors involved.

Mr. Franklin is with Savoisienne Ateliers de Constructions Électriques de la Compagnie Général d'Électricité, and was formerly with the English Electric Company.

(2) METHODS OF SEALING

The exposure of transformer oil to the atmosphere causes oxidation of the oil at transformer operating temperatures. This leads to the formation of acids and sludge and places a limit on the life of the oil which is usually very much less than that of the rest of the transformer. Attempts have therefore been made to eliminate the effects of oxidation by sealing off the oil in the transformer from the atmosphere.

Some of the constructional methods employed are:

(*a*) The use of metal bellows capable of expanding and containing the oil under all permitted conditions of load; this method is confined to small transformers.

(*b*) French engineers are experimenting with nitrogen-filled Neoprene reservoirs connected to the top of the expansion vessel. As the oil expands with rise in temperature the nitrogen from the vessel is forced into the Neoprene reservoir.

(*c*) One of the several systems in use in America for large transformers has the expansion space directly above the oil in the tank; this space is filled with nitrogen at a pressure of not less than about $0 \cdot 5$ lb/in^2 by means of a high-pressure bottle through suitable reducing valves. The transformer cover is sometimes welded on to achieve freedom from leaks.

(*d*) A transformer may be of normal construction and then sealed, but provided with a vessel or expansion space large enough to limit the gas pressures to a reasonable value; this expansion vessel or space may be initially filled with air or nitrogen.

The calculations in the following Sections apply to type (*d*), and although reference is frequently made to an expansion vessel the calculations are clearly applicable where a separate vessel is not employed.

(3) SIMPLE PRESSURE RELATIONS NEGLECTING THE EFFECTS OF GAS SOLUTION IN THE OIL AND THE CHEMICAL REACTION OF OXYGEN WITH THE OIL

If a transformer is tightly sealed and on load, pressures will be set up by the expansion of the oil. If the oil had no effect on gas in the expansion space these pressures would be determined from simple relations of volume and temperature, the maximum pressure being

$$p_5 = \frac{p_s y T_{a2}}{T_{a1}\{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\}} \quad . \quad . \quad (1)$$

These simple pressure values are plotted in Fig. 1 and they are of interest as being the maximum that can occur. It should be noted that in all equations $\alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)] \leqslant y$.

The oil, however, does have an effect on the gas in the expansion space, the gas being absorbed and in certain cases reacting chemically. This is responsible for large deviations of pressure from those given by the above expression. In order to understand the behaviour of sealed transformers, it is first necessary to have some knowledge of gas solution in oil.

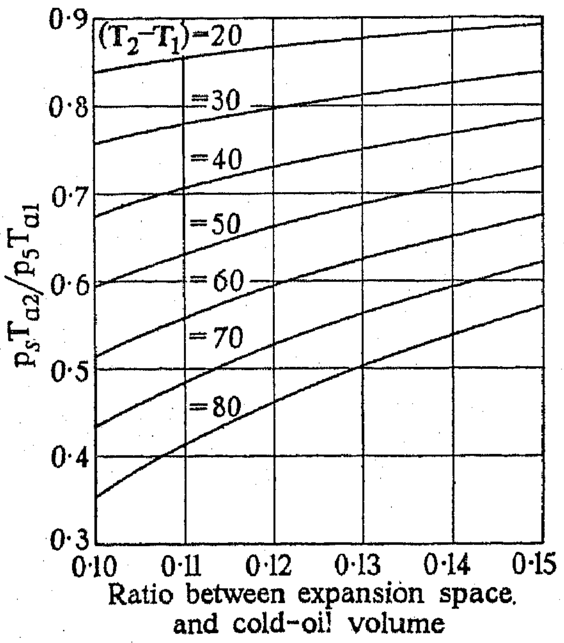

Fig. 1.—Simple pressure relations.

(4) SOLUTION OF GAS IN OIL

Now, as already stated, transformer oil must clearly contain dissolved gases, the amount being determined by the oil, the nature of the gas and the partial pressure. Over the range of pressures likely to be encountered in sealed transformers the solubility of the gases in the oil changes in accordance with Henry's law[7,18] (i.e. the solubility at a given temperature is directly proportional to the partial pressures of the gas). Experiment shows that this relation is approximately true over a wide range of pressure.

Temperature has also an effect on the solubility, but the variation is small; although there is no general agreement, it is believed that with increasing temperature the solubility of nitrogen increases slightly, and for oxygen there is a small decrease over the temperature range considered.[9] With air, the variation of solubility with temperature is small enough to be neglected.

The coefficients of solubility vary with viscosity, being higher with lower-viscosity oils.

The average experimental values of the Bunsen coefficient (defined as the volume of gas reduced to 760 mm Hg and 0° C absorbed by unit volume of liquid at a partial pressure of 760 mm Hg) for various gases in transformer oil at 25° C are $0 \cdot 083$ for nitrogen, $0 \cdot 139$ for oxygen and $0 \cdot 0937$ for air. From these coefficients we obtain:

For nitrogen, $v_g = 0 \cdot 00565p$
For oxygen, $v_g = 0 \cdot 00945p$
For air, $v_g = 0 \cdot 00637p$

The constant in the relation will be called the solubility factor.

The rate of diffusion of gas into the oil under pressure, although dependent on the conditions of agitation, and the ratio between the surface exposed to the gas and the depth of the oil, can be fairly rapid. The reverse is not true, however, and it is well known that gas in solution in oil is very difficult to remove; usually the oil must be well agitated or broken up by spraying in a vacuum.

When the sealing medium in a transformer is air, the pressure will cause the constituent nitrogen and oxygen to pass into solution in the oil, although not in the same proportions as they exist in air, owing to their different solubilities. On the assumption that air contains 21% oxygen and 79% nitrogen, the law of partial pressures* shows that there will be $0 \cdot 0292$ cm^3 of oxygen and $0 \cdot 0645$ cm^3 of nitrogen in solution in each cubic centimetre of oil at normal pressure; the relative proportions are thus $31 \cdot 5$% and $68 \cdot 5$%.

However, this mixture of gases in solution will be referred to as "air" for simplicity.

The literature dealing with the effect of gas in solution on the volume of the oil is chiefly concerned with natural gas and crude oils, and shows that the change in volume is extremely small at very high pressures.[18] The pressures used in sealed transformers are comparatively low, and the solution of air in oil is considerably less than natural gas, so that change in volume can be neglected.

(5) THE EFFECT OF GAS SOLUTION ON THE PRESSURES

One of the effects of gas solution is to reduce the maximum pressure; as the oil temperature rises, oil expands and compresses the gas in the expansion space; because of this increased pressure, gas will dissolve in the oil, since the amount of gas in

* Dalton's law of partial pressures states that the pressure of a gas in a mixture is equal to the pressure it would exert if it occupied the same volume at the same temperature.

solution is proportional to the partial pressure; some pressure relief is therefore afforded. This process will continue until equilibrium is established between the partial pressure of gas above the oil and the partial pressure of gas in solution. When this is so the pressure will be

$$p_4 = \frac{p_s y + p_g Z}{W + Z} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $$Z = 0{\cdot}054 T_{a1} k k_1 [1 + \alpha(T_2 - T_1)] \quad . \quad . \quad . \quad (3)$$

$$W = T_{a1}/T_{a2}\{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\} \quad . \quad (4)$$

Consider now the effect of switching off the transformer and allowing it to cool; the oil will contract and the pressure in the expansion space will fall. It may be imagined that the original sealing pressure p_s will be reached as soon as the transformer temperatures have dropped to T_{a1} and T_1, but this is not so for two reasons. One is that the oil at the time of sealing may be unsaturated at the sealing pressure, in which case it is able to absorb more gas in solution at this pressure and in doing so reduces the pressure in the expansion space. Secondly, experiment shows that even if the oil is saturated at the time of sealing, after a period of operation the gas absorbed by the oil during this period remains for the most part in solution when the transformer is cooled. The result is that the pressure when cooled after a period of operation is given by

$$p_2 = \left\{p_s W + Z\left[p_s(1 - k_2) + \frac{p_g W k_2}{y}\right]\right\}\frac{1}{W + Z} \quad . \quad (5)$$

The fraction k_2 depends on the time of cooling and on the physical construction of the transformer; it can be determined experimentally and is generally near to unity on account of the slow release of excess gas in solution.

At this point, if the transformer is left standing cold for a long time it may be that, owing to a very slow release of excess gas from the oil, the pressure will rise; and if the oil eventually ceases to be supersaturated the pressure will become

$$p_b = \frac{p_s y + p_g Z_1}{y + Z_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $Z_1 = 0{\cdot}054\ T_{a1} k k_1$.

Should the value of p_g at the time of filling be equal to p_s, then, of course, p_b will become equal to p_s.

(6) COMBINED EFFECT OF GAS SOLUTION AND CHEMICAL REACTION OF OXYGEN WITH OIL

Yet another factor in the determination of pressures is the chemical reaction of oxygen in the system with the oil. Oxygen may exist in solution in the oil at the time of filling, and also in the expansion space if this is filled with air at the moment of sealing. After a period of operation all this oxygen will disappear in the chemical reaction. The time taken for this to happen depends on many factors, among the most important being the operating temperature of the oil. Much investigation has and is being made to determine factors affecting the rate of oxidation of oil. Hill[10] and Ford[11] have investigated the rates of oxidation in sealed transformers, and Fig. 2 shows the rate of reaction of oxygen in a 100-kVA sealed transformer with the expansion space directly above the oil.

It is estimated that about $6{\cdot}5\ \text{cm}^3$ of oxygen (at normal pressure and temperature) per gramme of oil is required to produce a neutralization number of 1.* This corresponds to $4{\cdot}27\ \text{ft}^3$ of air per gallon of oil, or a ratio of about 27 : 1 between the volumes of air (at normal pressure and temperature) and oil; this is nearly 200 times the ratio actually found in sealed transformers, from which it may be concluded that there is too little oxygen in the system of a sealed transformer to cause oil deterioration.

* The acidity of oil is measured in terms of the weight of potassium hydrate in milligrammes required to neutralize the acid in 1 g of oil. A neutralization number of 1 indicates that 1 mg of potassium hydrate is necessary for this.

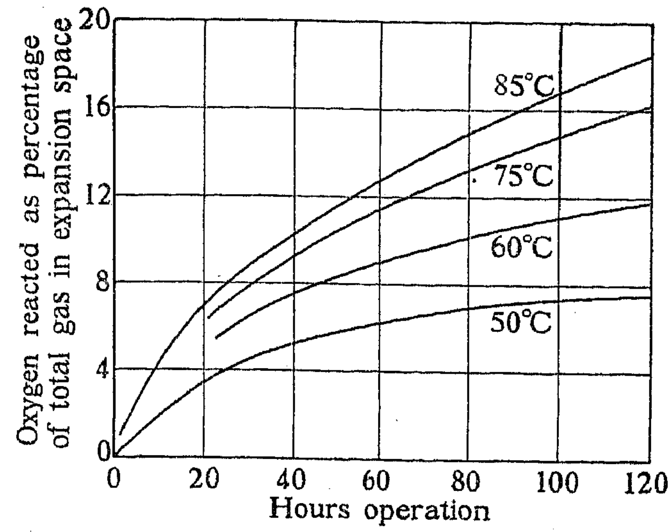

Fig. 2.—Rate of chemical reaction of oxygen.

The effect of the loss of oxygen is to lower the pressures, and the following pressure relations apply: the maximum pressure whilst loaded will be

$$p_3 = \frac{p_s y(1 - k_{ex}) + 0{\cdot}78 p_g Z}{W + Z} \quad . \quad . \quad . \quad . \quad (7)$$

while minimum pressure when cooled, but with excess gas in solution, is given by

$$p_1 = \left\{p_s W(1 - k_{ex}) + Z\left[p_s(1 - k_2)(1 - k_{ex}) + \frac{0{\cdot}78 p_g W k_2}{y}\right]\right\}\frac{1}{W + Z} \quad . \quad . \quad . \quad . \quad (8)$$

Once again, if the transformer is left at ambient temperature for a long period, and if during this time all excess gas in solution is released, the pressure will return to

$$p_{b1} = \frac{p_s y(1 - k_{ex}) + 0{\cdot}78 p_g Z_1}{y + Z_1} \quad . \quad . \quad . \quad (9)$$

From the equations it is obvious that, if the pressure of the gas in solution is low at the time of sealing, very low pressures will be reached when the transformer is cooled after a period of operation at maximum temperature.

The slight variation of solubility with temperature has been neglected. For air the error is negligible, but for nitrogen there may be an error of the order of 5%.

Figs. 3(*a*) and 3(*b*) show the calculated pressures based on the British Standard temperature-rise of 50° C in the top oil with a maximum ambient of 40° C. The average oil temperature-rise is taken as 74% of the top-oil temperature-rise, and

$$T_2 - T_1 = 62^\circ\ \text{C};\ k = 0{\cdot}00565\ \text{(nitrogen)},\ 0{\cdot}00637\ \text{(air)}.$$
$$T_v = 65^\circ\ \text{C};\ k_1 = 1.$$
$$T_{a2} = 65^\circ\ \text{C};\ k_2 = 1.$$
$$T_{a1} = 15^\circ\ \text{C};\ \alpha = 0{\cdot}00081\ \text{per deg C}.$$

(7) VARIATION IN ELECTRIC STRENGTH OF THE OIL

Operating conditions occur in sealed transformers which are not normally found in transformers allowed to breathe, in that the oil is subject to variations in pressure and in the amounts of gases in solution. These quantities have been seen to depend, among other things, on the condition of the oil when the transformer is sealed, as well as on volumetric relations, temperature rise and the arrangement of the expansion space in relation to the main body of oil.

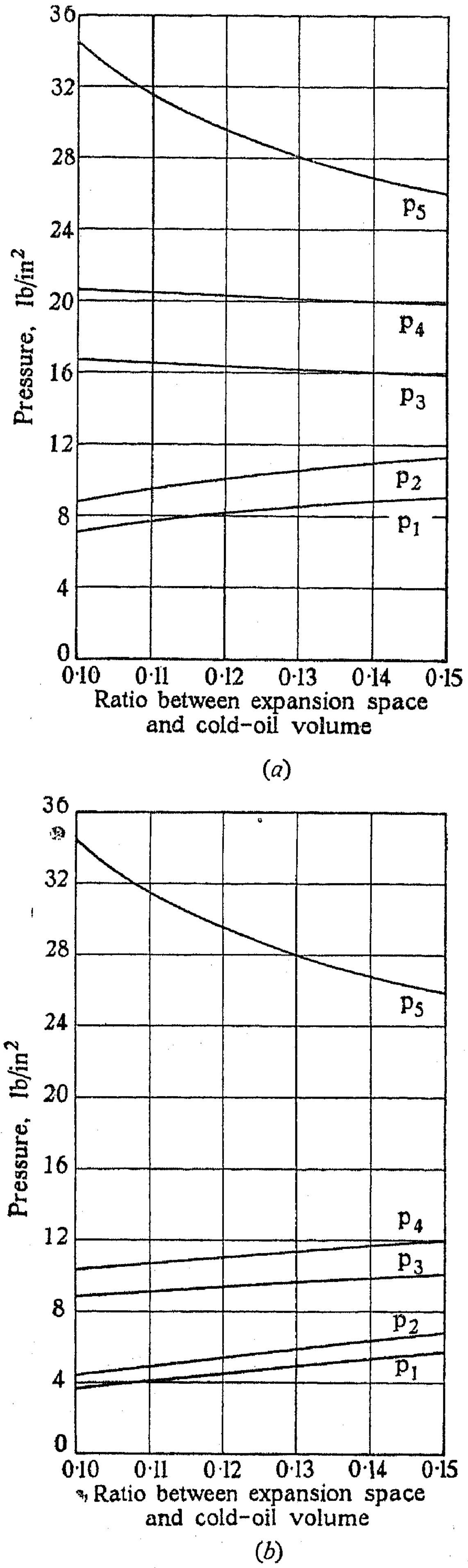

Fig. 3.—Pressures in the expansion space.

(a) Transformer filled with air-saturated oil and sealed with air.
(b) Transformer filled with thoroughly degassed oil and sealed with air at once.

The combinations and variations of pressures with load are summarized as follows:

(a) As the temperature of the oil rises the partial pressures of gases above the oil increase. With this, gases go into solution and their partial pressures rise at a rate depending on the physical arrangement of the expansion space and on the partial pressures of gases above the oil. At full temperature the partial pressures of gases above oil and of gases in solution may be equal or nearly so.

(b) As the oil temperature is lowered the partial pressures of gases above the oil are reduced, but those of gases in solution may change only slightly if at all, since these are not readily released. Thus the partial pressures of gases in solution exceed those of gases above the oil by increasing amounts, the difference being greatest when the transformer is cold. The total pressure of gases in solution at this stage may be several pounds per square inch above atmospheric pressure and that of the gases above oil may be several pounds per square inch below atmospheric pressure. The pressure differences are shown in Figs. 4(a) and 4(b).

An examination of published work on the variation of electric strength of oil with pressure shows how difficult it is to correlate the results of numerous experimenters obtained with different

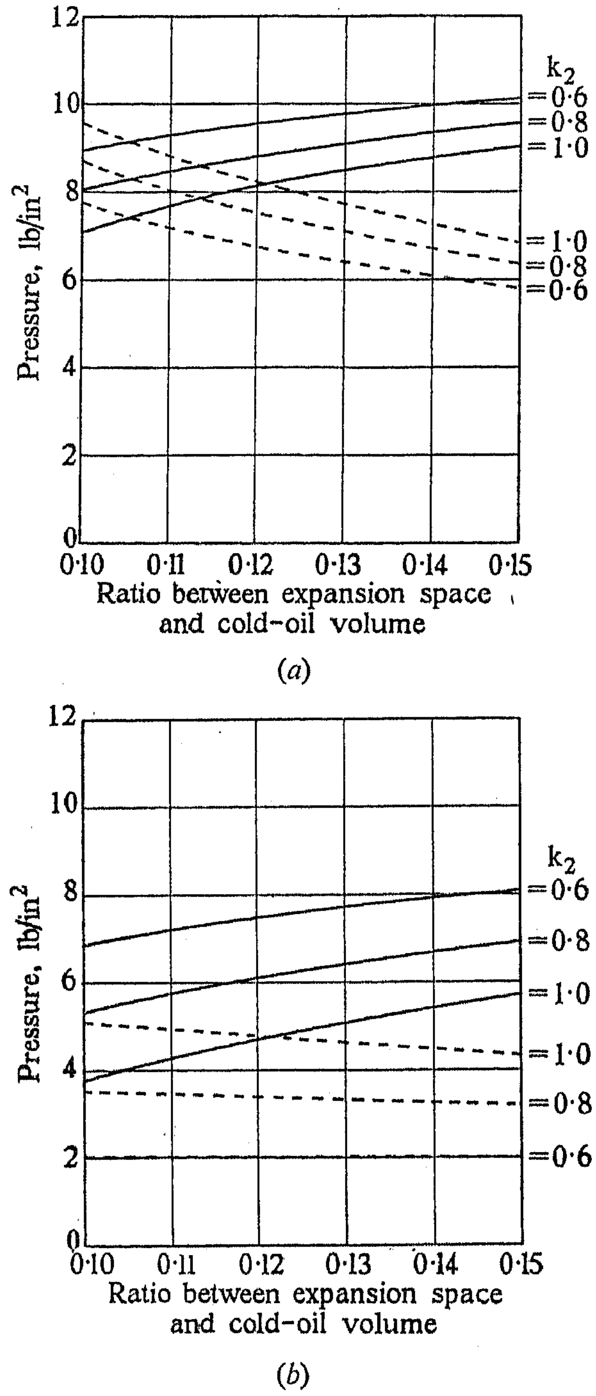

Fig. 4.—Minimum pressures in the expansion space and excess pressure of gas in solution.

——— p_1.
— — — Excess pressure of gas in solution.

(a) Transformer filled with air-saturated oil and sealed with air.
(b) Transformer filled with thoroughly degassed oil and sealed with air at once.

experimental techniques using dissimilar electrodes, gaps and circulation arrangements. For case (a) there seems to be a fair measure of agreement, but for case (b)—the most important in sealed transformers—the data are too scanty to be conclusive, and there is a pressing need for more investigation under these conditions.

One of the theories of breakdown in oil assumes that the presence of gas in suspension is responsible for the initiation of breakdown, the bubbles of gas becoming ionized in the field

followed by breakdown. It is also thought that the gas is changed from solution to suspension form by the effect of electric stress. It is therefore reasonable to assume that breakdown will be affected if pressure affects the availability of gas in suspended form.

In order to obtain an idea of the effect of pressures on breakdown, the results of six experimenters are collected in Table 1.

Table 1

BREAKDOWN VALUES

Experimenter	Simultaneous change of p_4 from	p_4 to	p_g from	p_g to	Change in breakdown strength from	Change in breakdown strength to	Change in breakdown strength
	cm Hg	cm Hg	cm Hg	cm Hg	kV	kV	%
Thomas[19]	76	760	76	760	173	305	+76
Kock[16]	0	760	0	760	100	162	+62
Clark[7]	76	5	76	5	40	28	−30
Race[12]	76	10	76	10	590	420	−28
Race[12]	76	152	0	76	No change		
Hoover & Hixson[13]	76	2·1	76	2·1	26	18	−31
Hoover & Hixson[13]	2·1	2·1	76	2·1	11	18	+64
Hoover & Hixson[13]	76	2·1	76	76	26	11	−58
Koppelman[15]	1·1	1·1	76	1·1	250	350	+40

For case (*a*) there is an increase in strength, but for case (*b*) there is evidence [13,15] of a serious fall in electric strength which, at reduced total gas pressure above the oil with excess total pressure of gas in solution, is more than occurs with reduced balanced pressures (i.e. oil saturated only).

The description of tests made by Kock[16] and by Thomas[19] suggest that breakdowns were obtained under pressure equilibrium (total pressure of gas above oil equal to that of gas in solution), since in each case compressed gas was used to raise the pressure.

Information given by Clark[7] about the method of carrying out tests is incomplete, but it appears that breakdown values were obtained at pressure equilibrium and also for conditions where the total pressure of gas in solution was varied whilst that on the oil was maintained at one atmosphere. The curve for balanced-pressure conditions is shown in Fig. 5.

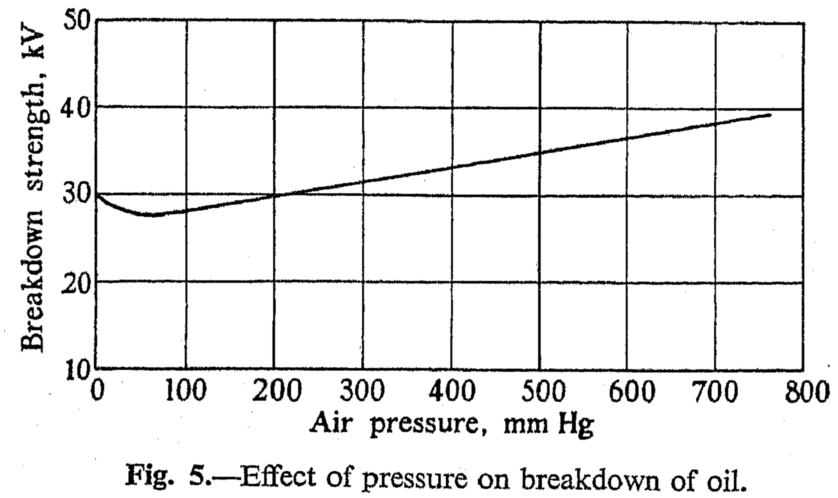

Fig. 5.—Effect of pressure on breakdown of oil.

In a series of tests in which the total pressure of gas in solution was varied and that on the oil kept at one atmosphere above the total pressure of gas in solution, Race[12] found that the electric strength of the liquid did not vary. These findings disagree with those of Clark.[7] On examination of the plotted points of the tests it is possible to obtain more information about electric strengths at balanced pressures which agrees closely with Clark's information.

Hoover and Hixson[13] show a clear and large difference between breakdown at pressure equilibrium and breakdown with excess gas in solution. Unfortunately, only one value of reduced pressure is considered.

Koppelman[15] has illustrated his interesting observations with sketches showing bubble formation under electric stress with excess gas in solution. Again, figures for only one reduced pressure are given.

Applying the limited available information to the case of a sealed transformer filled under 28 in of vacuum and sealed with air, with $y = 0\cdot10$ and $k_2 = 1$, from Fig. 4(*b*) the total pressure of gas on oil when cold is $3\cdot8$ lb/in^2 and the excess pressure of gas in solution is 5 lb/in^2. For a balanced pressure reduction to $3\cdot8$ lb/in^2 the drop in electric strength would be about 25%. For an excess total pressure of gas in solution of 5 lb/in^2 there would be a further drop in electric strength, and if we assume this to be proportional to the total excess gas in solution, it might be estimated from Hoover and Hixson's figures as being $39 \times (5/14\cdot3) = 13\cdot6\%$. Thus the total drop would be approximately 35%. This is obviously undesirable and must be reduced by measures suggested later.

The significance of a reduction in electric strength after test may be illustrated by the following. Imagine the transformer to have passed by a very small margin of safety a separate-source test during which the winding was stressed to twice the working voltage for 1 min at twice the normal frequency. If the infinite-time breakdown value at normal frequency is said to be 73% of the 1-min breakdown value at twice the normal frequency, then for a reduction in the electric strength of the oil of $r\%$ after test the infinite-time breakdown value would be $(1 - r/100)(2 V_w \times 0\cdot73)$, where V_w is the working voltage. From this, if $r > 31\cdot5\%$, the breakdown value will be less than working voltage and premature breakdown would be likely. This figure should be considered in the light that one might expect a small reduction in the oil breakdown value from causes other than reduced pressure, such as contamination of the oil with fibres from the windings.

(8) NEGATIVE PRESSURES AND POSSIBLE METHODS OF REDUCTION

Remarkably large negative pressures can occur in sealed transformers unless special precautions are taken. These negative pressures may be undesirable, because

(*a*) If the negative pressure is high there may be a serious reduction in the electric strength of the oil.

(*b*) With a gasket joint under oil the chance of a leak of air into the transformer is greater than that of a leak of oil from out of the transformer, and negative pressures would tend to produce the former, associated with bubbles in the oil. It is thus easier to produce a leak-free transformer having at all times a positive pressure.

Negative pressures may be avoided theoretically by sealing the transformer initially under pressure, but the disadvantage of this is that this increases the maximum possible pressures at full load. It is more practical if nitrogen is used.

(8.1) Valves

Some manufacturers fit valves to limit the upper and lower pressures. Operation of the low-pressure valve would continue with heating and cooling until the maximum pressure at full temperature was equal to

$$\frac{\text{low pressure valve setting} \times y}{W}$$

when both k_1 and k_2 are unity.

The oil would, of course, become supersaturated with gas in solution, but the fitting of a low-pressure valve offers a practical solution to the prevention of low pressures. The provision of a valve to release high pressures becomes necessary when a low-pressure valve is fitted, because, if the transformer were to be subject to extremely low temperatures when not operating, the low-pressure valve would permit the intake of air in such quantity that the pressures would be too high when the transformer was again loaded and the oil temperature raised.

(8.2) Vacuum Filling

Filling transformers under vacuum, or filling them with degassed oil under vacuum, means that after the filling the oil is gas deficient (i.e. p_g is low) and large negative pressures will tend to occur. A method of reducing these in this case is to put back air, or—preferably—nitrogen, into the oil before sealing by exposing a large surface area of the oil to the air or nitrogen at atmospheric or higher pressure and then circulating the oil. Experiments show that the mere exposure of still oil to the gas is not effective in large transformers, except perhaps over extremely long periods of exposure.

It must here be pointed out that absence of pressures below atmospheric does not mean that there is no reduction in the electric strength, since conditions where the partial pressure of gas in solution is greater than that of gas above oil still exist. Lack of information on breakdown under these conditions prohibits further comment.

(9) POSITION OF EXPANSION SPACE

There arises the question whether it is better to encourage the gas-solution process or not. For example, if the gas space is directly above the main body of oil, gas will go into solution under pressure in large quantities even before peak temperature is reached in a first heat run. This is demonstrated in Fig. 6.

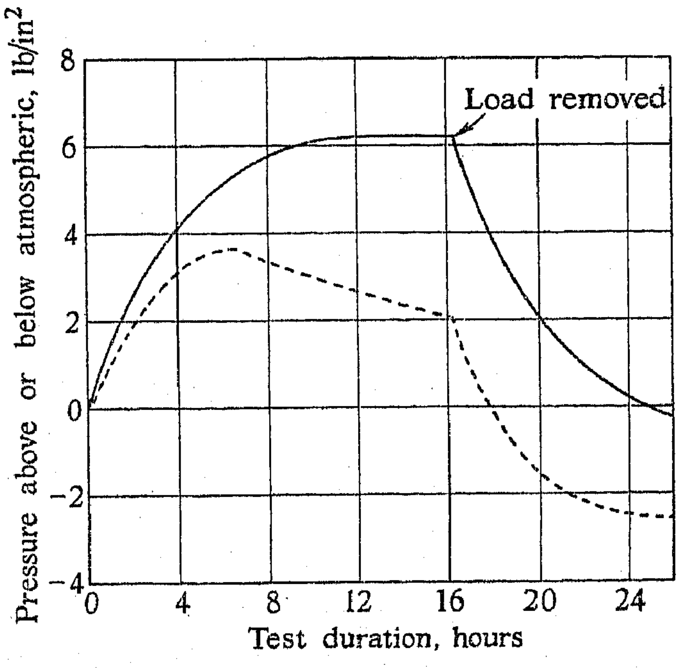

Fig. 6.—Calculated and test pressures.

——— Calculated.
— — — Test.

On the other hand, if a separate vessel is employed, connected as usual by a long pipe, the gas-solution increase with pressure is confined initially to the oil in the expansion vessel but will gradually involve the whole of the oil, even if only by mixing of the oil in the expansion vessel with that in the main tank during heating and cooling cycles.

The answer is that, if the whole of the oil is to be eventually involved in the gas-solution process, it may be better to take advantage of the relief of maximum pressure afforded by hastening the process, and this can be achieved even if a separate expansion vessel is used. This does not apply, however, when a low-pressure valve is fitted, because even if absorbtion of gas by the oil takes place rapidly with the associated upper-pressure relief, the top pressure may rise with repeated heating and cooling and operation of the valve.

If an expansion vessel is fitted there will be an increase in the static head of oil at any point within the main tank. The lowest pressure to occur in the oil will be p_1 + static head. In large transformers with separate cooling banks the static head acting on the highest level in the main tank may be as high as 4 lb/in², so that there is thus some alleviation of conditions which lead to reduced electric strength of the oil.

(10) THE FUNCTION OF THE BUCHHOLZ DEVICE

Because of gas transfer to the main body of oil and its possible slow release in the top of the main tank under certain conditions, there arises the question of maloperation of the Buchholz device if one is used. Operation should, however, be normal if the ratio between the maximum excess pressure of gas in solution and the static head in the top of the main tank is not high.

(11) CONCLUSIONS AND ACKNOWLEDGMENT

From the foregoing it is concluded that filling and sealing procedures largely determine the operating pressures in sealed transformers; in those filled under vacuum, filled with degassed oil, or both, there may be danger from a reduction in electric strength of the oil due to the combination of large negative pressures and excess amounts of gas in solution. If a large reduction in electric strength is to be avoided, steps must be taken to limit the negative pressures. Trouble has been experienced from a drop in electric strength,[17] and research should be carried out to determine accurately the variation under conditions peculiar to sealed transformers. It is suggested that the tests be made for oil with different degrees of contamination with fibres, since it is thought that the greater the contamination the greater the effect of supersaturation and external pressure on breakdown.

Negative pressures may be reduced by sealing the transformer under pressure (although in some cases this is not very practical), or by pressure-limiting valves; alternatively, after filling and before sealing, air or gas may be used to replace the air removed during or before the filling process, nitrogen being the best gas for this purpose.

If there is a risk of very low ambient temperatures the need for action is more necessary, since the pressure when cold can be even lower than shown by the curves.

Finally, when designing the tank it must be remembered that the duty involved in withstanding repeated pressure variations is more severe than in a normal breather-type tank, which may be called upon to withstand vacuum only a few times (in the filling process) during the life of the transformer.

The author thanks the Director, Savoisienne, Ateliers de Construction de Transformateurs de la Compagnie Générale d'Électricité, for permission to publish the paper.

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then
$$p_5 = \frac{p_g v_e T_{a2}}{T_{a1}\{v_e - v_0\alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\}} \quad (13)$$

Dividing numerator and denominator by v_0 and putting $v_e/v_0 = y$ gives

$$p_5 = \frac{p_s y}{T_{a1}/T_{a2}\{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\}} \quad (14)$$

(13.1.2) **Determination of Equation for p_4.**

At pressure p_4 (with oil saturated) the quantity of gas absorbed into solution from the expansion space is

$$\frac{(p_4 - p_g)}{p_4} \times 0{\cdot}054\, T_{a2}kk_1v_0[1 + \alpha(T_2 - T_1)] \quad . \quad (15)$$

(reduced to pressure p_4 and temperature T_{a2})

$$p_4 = \frac{p_5\{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\}}{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)] + \dfrac{(p_4 - p_g)}{p_4} \times 0{\cdot}054\, T_{a2}kk_1[1 + \alpha(T_2 - T_1)]} \quad . \; . \; . \; . \; . \; . \quad (16)$$

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(13) APPENDIX

(13.1) Derivation of Equations for Pressures

In all equations $\alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)] \leqslant y$.

(13.1.1) **Determination of Equation for p_5.**

The volume of oil displaced from the main tank if the average oil temperature variations were $(T_2 - T_1)$ would be

$$v_0\alpha(T_2 - T_1) \quad . \; . \; . \; . \; . \; . \; . \quad (10)$$

but, owing to the remote position of the expansion chamber, the temperature of the oil therein may be T_v; thus the volume of displaced oil will now be

$$v_0\alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)] \quad . \; . \; . \quad (11)$$

and the volume of the expansion space will be reduced from v_e to

$$v_e - v_0\alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)] \quad . \; . \quad (12)$$

But from eqn. (14),

$$p_5 = \frac{p_s y}{T_{a1}/T_{a2}\{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\}}$$

Thus after substituting for p_5

$$p_4 = \frac{p_s y}{W + \dfrac{(p_4 - p_g)}{p_4}Z} \quad . \; . \; . \; . \quad (17)$$

where $W = T_{a1}/T_{a2}\{y - \alpha(T_2 - T_1)[1 - \alpha(T_2 - T_v)]\}$. (18)

and $Z = 0{\cdot}054\, T_{a1}kk_1[1 + \alpha(T_2 - T_1)]$ . . (19)

Finally $$p_4 = \frac{p_s y + p_g Z}{W + Z} \quad . \; . \; . \; . \; . \; . \quad (20)$$

(13.1.3) **Determination of Equation for p_2.**

If the transformer is cooled the volume of gas removed from the expansion space and remaining in solution at pressure p_2 is

$$\frac{(p_4 - p_g)}{p_2} \times 0{\cdot}054\, T_{a1}kk_1k_2[1 + \alpha(T_2 - T_1)]v_0 \quad . \quad (21)$$

(volume reduced to pressure p_2 and temperature T_{a1})
Then

$$\frac{p_2}{p_s} = \frac{v_e}{v_e + \dfrac{(p_4 - p_g)}{p_2} \times 0{\cdot}054 T_{a1}kk_1k_2[1 + \alpha(T_2 - T_1)]v_0} \quad . \quad (22)$$

$$= \frac{y}{y + \dfrac{(p_4 - p_g)}{p_2}k_2Z} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (23)$$

and $$p_2 = p_s - (p_4 - p_g)k_2Z/y \quad . \; . \; . \; . \quad (24)$$

But from eqn. (20) $$p_4 = \frac{p_s y + p_g Z}{W + Z}$$

Substituting for p_4 in eqn. (24) gives

$$p_2 = \left\{p_s W + Z\left[p_s(1 - k_2) + \frac{p_g W k_2}{y}\right]\right\}\frac{1}{W + Z} \quad . \quad (25)$$

(13.1.4) **Determination of Equation for p_b.**

At pressure p_b the volume of gas in solution removed from the expansion space is

$$\frac{(p_b - p_g)}{p_2} \times 0{\cdot}054T_{a1}kk_1v_0 \quad . \quad . \quad . \quad . \quad (26)$$

(reduced to pressure p_2 and temperature T_{a1})

$$\frac{p_b}{p_s} = \frac{v_e}{v_e + \frac{(p_b - p_g)}{p_b} \times 0{\cdot}054T_{a1}kkv_0} \quad . \quad . \quad (27)$$

and
$$p_b = \frac{p_s y - p_g Z_1}{y + Z_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

where
$$Z_1 = 0{\cdot}054T_{a1}kk_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

(13.1.5) **Determination of Equation for p_3.**

The effect of the chemical reaction of oxygen is to change the value of p_s in eqn. (20) to $p_s(1 - k_{ex})$. The value of p_g will also be modified to $0{\cdot}78p_g$ for the following reasons.

Suppose that the volume of air (31% oxygen and 69% nitrogen) in solution at the time of sealing is $p_{ga}k_a v_0$, where p_{ga} and k_a are respectively the partial pressure of air in solution and the solubility constant for air. If the oxygen disappears by chemical reaction, the volume of gas in solution (nitrogen) is $0{\cdot}69p_{ga}k_a v_0$ and this is equal to $p_{gn}k_n v_0$, where p_{gn} and k_n are respectively the partial pressures of gas in solution after reaction of oxygen and the solubility constant for nitrogen.

Thus
$$p_{gn} = p_{ga}\frac{k_a}{k_n} \times 0{\cdot}69 = 0{\cdot}78p_{ga} \quad . \quad . \quad . \quad (30)$$

Therefore
$$p_3 = \frac{p_s y(1 - k_{ex}) + 0{\cdot}78p_g Z}{W + Z} \quad . \quad . \quad . \quad (31)$$

p_g is, of course, the partial pressure of gas in solution when the transformer is sealed and Z has a value appropriate for nitrogen.

(13.1.6) **Determination of Equation for p_{b1}.**

The same reasoning applies as above

and $p_1 =$

$$\left\{p_s W(1 - k_{ex}) + Z\left[p_s(1 - k_2)(1 - k_{ex}) + \frac{0{\cdot}78p_g Wk_2}{y}\right]\right\}\frac{1}{W + Z} \quad . \quad . \quad . \quad . \quad (32)$$

(13.1.7) **Determination of Equation for p_b.**

Again modifying as above

$$p_{b1} = \frac{p_s y(1 - k_{ex}) + 0{\cdot}78p_g Z_1}{y + Z_1} \quad . \quad . \quad . \quad (33)$$

(13.2) Estimation of the Effect of Tank-Wall Deflection on Pressure

Under pressure the transformer tank wall will deflect, causing increase in volume under positive pressure and decrease under negative pressure. The increase or decrease will depend on many things, such as relative dimensions, method and degree of stiffening, general shape and other factors which make exact solution impossible. However, if certain simplifying assumptions are made, a very approximate idea of the effect on the pressure can be obtained.

Assume that

(*a*) The tank walls deflect as encastré beams.
(*b*) The change in volume is $\delta L/2$ per inch width of wall, L being the wall length and δ being the maximum deflection.
(*c*) The maximum deflection occurs along the whole wall length.
(*d*) The displacement of the transformer core and coils is equal to the oil contained in the radiators, and that the radiators are of a type that do not expand under pressure.
(*e*) The sides, bottom and top deflect, and the tank has height L, width $L/2$ and length L.

Since in practice the maximum deflection does not take place over the whole wall length, the calculation based on this assumption would give high results, but at the same time the value $\delta L/2$ for increase in volume per inch width would give low values. The two discrepancies would tend to cancel, and this is the assumption made in the calculations.

$$\delta = \frac{\omega L^3}{384EI} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

and since $M = \frac{\omega L}{12}$ and $I = \frac{My_1}{f}$

$$= \frac{L^2 f}{32Ey_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

if $f = 20 \times 10^3$ and $E = 30 \times 10^6$

$$\delta = \frac{3{\cdot}13L^2 \times 10^{-5}}{y_1} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

The sum of the wall widths (including top and bottom) is $4L$ and the volume of the tank is $0{\cdot}5L^3$; the change in volume as a fraction of the original volume is then

$$\frac{\delta L}{2} \times \frac{4L}{0{\cdot}5L^3}$$

Substituting for δ and taking L as 100 in and y_1 as 2 in, the change in volume is 0·42%. The factor $y - \alpha(T_2 - T_1)$ in eqn. (1) will be affected and will become

$$[y - \alpha(T_2 - T_1) + 0{\cdot}0042] \quad . \quad . \quad . \quad . \quad (37)$$

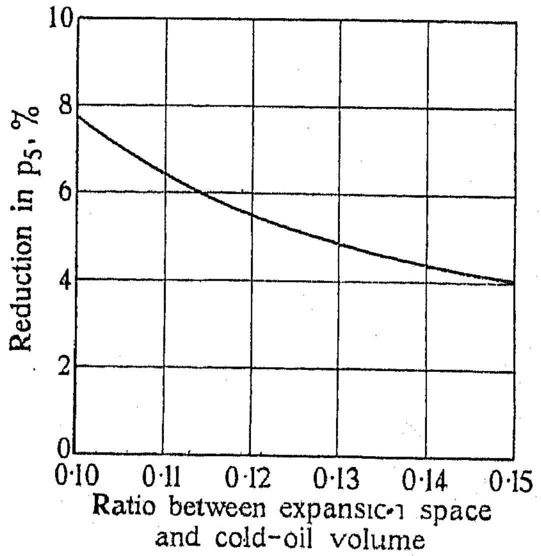


Fig. 7.—Effect of tank-wall deflection on the pressure.

The percentage reduction in p_5 is plotted for different values of expansion space in Fig. 7. It is emphasized that the simplifying assumptions are broad and the effect will vary greatly with construction.

DISCUSSION BEFORE THE SUPPLY SECTION, 26TH JANUARY, 1955

Mr. L. H. Welch: The author's object is to attain a higher degree of oil preservation than is provided by the well-known conservator, but I wonder whether this is really needed, and whether it is necessary to have elaborate and expensive apparatus, such as nitrogen cylinders connected to the tank, to do the job. I am interested in small distribution transformers and in larger transformers up to 15 or 20 MVA. For the larger ones I am satisfied to rely on a conservator and a good oil, and I am sure that any oil to B.S. 148: 1951 will last as long as the transformer if it has a conservator, and some of the good oils are also likely to last in the smaller transformers, which have no conservators but a suitable dehydrated breather.

The London Electricity Board have about 1 000 sealed-type transformers, some over 20 years old. The majority are of the author's type (*a*), i.e. small transformers with no gas of any kind; they are completely filled with oil and have some form of device —they are not all of one manufacture—which allows the oil to expand. The only trouble experienced is splitting of the expansion device during rather severe overloads, but there has been no trouble from acidity, etc.

We also had some 250 of type (*d*), the type which has some air above the oil; they were bought before nitrogen filling was popular, and I think that almost without exception they have been scrapped. They developed extreme acidity and tanks and covers were corroded badly, probably owing to what is revealed by the curves in Fig. 6, which show a negative pressure of nearly 3 lb/in^2 at certain times. Gaskets will not withstand such negative pressures for any considerable period, and this results in limited and restricted breathing, which is a very bad condition.

We have had transformers with tanks which have rusted through completely and with acidity figures up to 13 or 14, but it is difficult to see where the $4\frac{1}{4}$ ft^3 of air per gallon of oil needed to produce an acidity of unity comes from when the gasket is under oil and remains satisfactory for retaining oil, although some air must get through. If sealed transformers of this kind are used nitrogen should be employed, but air may still get in and cause trouble. New York engineers are so mistrustful of gaskets that for small distribution transformers they weld the transformer tops on to the tanks, then put nitrogen in and hope that it will last.

The author says that negative pressures may be undesirable; I would go much further and say that negative pressures are extremely undesirable, and that, if they are allowed to occur, air will get into the transformer, producing a condition which promotes maximum acidity. It is interesting to note that considerably less acidity is produced if the transformer is ventilated.

The Americans like nitrogen filling, but they are inclined to take an idea to excess, and it is very doubtful whether the extra expense can be justified on distribution transformers. I agree that some means of keeping a positive pressure within a transformer is essential, but the ordinary conservator does this adequately and economically; it keeps a small head of oil on the transformer and maintains a positive pressure, which is the secret of keeping out anything that is not wanted inside.

The breakdown voltage is lowered by dissolved gas, but this is of little significance compared to the low values that can be and have been produced by water and fibres. In any case, breakdowns of transformers from this cause are almost unknown.

Mr. L. C. Richards: Has the author any practical experience of operating and maintaining transformers with this type of sealing? From a practical aspect I have found that similar transformers filled with oil at 15° C and designed for a maximum tank pressure of 8 lb/in^2 will function quite satisfactorily over a temperature range from −5° C to +90° C with pressures inside the tank from −2 to +8 lb/in^2 if air solubility is neglected, and from −4 to +6 lb/in^2 if this factor is taken into account. Such pressure variations are quite moderate from the point of view of tank design.

It is less easy to determine the practical effects of pressure variations on the breakdown value of the oil, and much more experimental work is required before reliable data on this point can be made available. It is accepted that negative pressures are bad from a dielectric aspect, but there should be no difficulty with ratings up to 1 MVA and 33 kV. For higher ratings, when the transformer is generally filled under vacuum and with de-aerated oil, this question of the negative pressure obviously becomes more important, as the oil is in a condition more readily to take air into the solution, and I do not think that this type of sealed transformer would be at all suitable. If a sealed transformer is really required it will pay to follow the American method of keeping a small positive pressure of nitrogen above the oil, this being fed in from a high-pressure bottle through suitable reducing valves.

I was surprised to see in Section 8 that "With a gasketed joint under oil the chance of a leak of air into the transformer is greater than that of a leak of oil from out of the transformer." The reverse has been my experience.

The greatest danger with a sealed transformer of the (*d*) type arises from the possibility of restricted breathing. This has already been referred to, and it is almost the only thing in transformers which is of really great importance. If there is restricted breathing, due to a small amount of air being sucked in either through a gasket which is above the oil or a badly welded joint, severe oxidation of the oil will take place, with the rapid development of acidity in the oil and corrosion of the metal parts above the oil. An alarm device cannot be relied upon to deal with this matter, since the transformer may be in a remote position and not subject to frequent inspection.

Although we have not had examples of this with sealed transformers, we have had one or two bad cases of restricted breathing at points where low-voltage cables pass through a close-fitting wooden bush. This can cause acidity to develop to such an extent that the windings and insulation cannot be cleaned, and holes may even be corroded in the tank or the cover.

I am also concerned by the reference in Section 8.1 to the fitting of high-pressure and low-pressure valves, with the idea that, if the pressure is too high the valve will discharge, while if it is too low air can be sucked in to stop a negative pressure developing. This seems to me to be perilously near to restricted breathing, which is so detrimental to the satisfactory operation of transformers.

I consider that the best method of operating small transformers is to have completely free breathing, with a vent at each end of the tank so that air can flow across the surface of the oil, while for large transformers I am convinced that the oil conservator provides the most economical as well as the most satisfactory arrangement.

Mr. C. N. Thompson: I assume that the principal objective of sealed transformers is to minimize oil deterioration; since the method seems likely to involve more expense than the normal construction, will the author compare the economics at, say, different ratings for normal and sealed transformers with other methods of combating oil oxidation? I am thinking here, not merely of nitrogen blanketing, but of the use of inhibited oils, which seem to offer technical advantages.

The author quotes a value of 6·5 cm^3 of absorbed oxygen per gramme of oil as corresponding to the development of an acidity

of 1 mgKOH/g; this figure refers strictly to oil oxidation with an excess of oxygen, which is the opposite case to that which we have here, i.e. limited oxygen availability. Our work at the Thornton Research Centre shows that with limited oxygen access a given oil will tend to produce more sludge at the expense of acids (whose formation is favoured under oxygen-excess conditions, although ventilation permits them to escape). There is also evidence that electrical properties, such as electric strength, d.c. resistivity and power factor may be impaired under reduced-oxygen-access conditions, perhaps because moisture cannot escape.

These facts should be borne in mind in the light of the author's conclusion that "there is too little oxygen in the system of a sealed transformer to cause oil deterioration," which may well be a dangerous generalization.

One of the main conclusions drawn from transformer trials at top-oil temperatures of 85–100°C is that, although the transformers are "dry" in the commercial sense, water is driven from the insulation under these conditions. We have desiccant breathers fitted by means of which we can weigh the water evolved as a function of time of operation, and we can also find evidence of lid-corrosion. Moreover, commercial impregnating varnishes sometimes dissolve in the oil at these high temperatures, giving sludge-like deposits. It is our view that many such instances of lid corrosion and sludging which have in the past been ascribed to oil oxidation are the result of insulation deficiencies and are quite unconnected with the properties of the oil.

If advantage is taken of the high stability of inhibited oil and transformers are operated at higher temperatures than now, more attention may have to be paid to the insulation, both as regards its oil-solubility characteristics and dehydration prior to use. These conclusions apply with equal force to hermetically-sealed or nitrogen-blanketed units, especially where the construction is such that moisture cannot be released to a desiccant breather or to the atmosphere.

In a sealed unit with air present, all the oxygen will eventually be consumed by the oil, especially if this is uninhibited, and, as the author points out, due allowance must be made for this in equilibrium pressure calculations. I gather from Section 8 of the paper that air is more likely to enter a unit under vacuum when there is a small leak, rather than oil to escape. This condition is, as Mr. Richards points out, less desirable from the dielectric and oxidation-stability aspects than one where a positive pressure is maintained.

As the author points out, there has not been a great deal of work published on the dielectric properties of oils under different conditions of gas saturation, and there is ample scope for research in this direction. He mentions that one of the theories of breakdown in oil assumes that the presence of gas in suspension is responsible for the initiation of breakdown, the bubbles of gas becoming ionized in the field followed by breakdown. "It is also thought," he says, "that the gas is changed from solution to suspension form by the effect of electric stress." In this connection I would draw attention to a recent paper* which contains some very interesting comments on this point.

Mr. A. T. Chadwick: Since most of the causes of trouble with oil in transformers come from the outer atmosphere, it is natural that some means should be sought to exclude atmosphere, and therefore to consider sealing as desirable. Against that is the wide range of temperature variation, which involves the provision of means of taking up expansion. Although ideally and theoretically it is so desirable, the practical application brings in its train questions of both a practical and an economic nature.

Experience of transformer practice over a long period shows that the simple conservator vessel has been almost universally accepted. One result has been that transformer makers have assumed that oil in a transformer is never in the ideal condition. This is accepted as a practical condition and regarded as sound policy. However, with tank sealing in some form or other the the results of temperature and pressure variation call for careful examination.

In a recent experience with a 7·5 MVA sealed transformer we found that during extreme temperature variations there was sufficient release of gas from the body of the oil to operate the Buchholz device when no internal fault had occurred. This occurred during a very cold night when the transformer load was very light and the oil temperature fell fairly rapidly. Subsequently we carried out some experiments with oil in two or three conditions of gas or air saturation and tested for bubble formation under various electric stresses and surface pressures. The oil was placed in a vessel with two electrodes spaced slightly apart, voltage was applied to the electrodes and a certain degree of vacuum to the top surface.

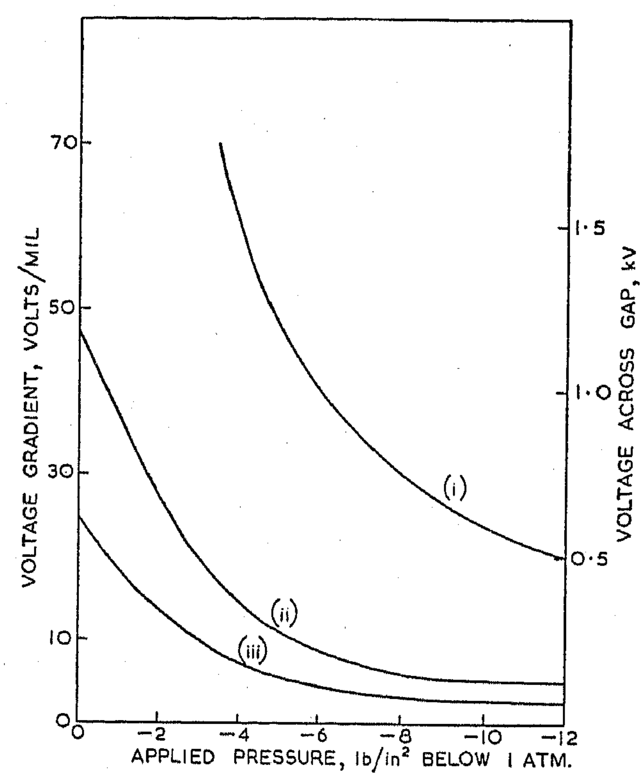


Fig. A.—Variation of bubble appearance potential with applied pressure for different gas saturation pressures.

Test gap, 0·025 in (3/16 in diameter spheres).
P_g = Gas saturation pressure in oil, lb/in² above 1 atm.
Region to the left of any particular curve is bubble free; to the right, bubbles will appear.

(i) $P_g = 0$.
(ii) $P_g = 0{\cdot}5\,\text{lb/in}^2$.
(iii) $P_g = 1{\cdot}0\,\text{lb/in}^2$.

Curve (i) in Fig. A is for the oil which has been subjected to the atmospheric degree of saturation. At the point where we have $-4\,\text{lb/in}^2$ of vacuum applied we notice that a formation of bubbles is given off from the oil with the application of about 60 volts/mil, which is a stress approximating to values occurring between connections, etc., in transformers.

From the above experience and the results of the laboratory tests it appears that, with the type of sealing dealt with in the paper, there exists both the possibility of operation of a gas-operated relay without any real fault in the transformer, as the result of bubble release under low internal pressure conditions, and the possibility of internal flashover along a rising stream of bubbles.

Dr. J. B. Higham: The electric strength of the transformer insulation is one of the most important special considerations for a designer of sealed transformers, and I agree that more

* Buchholz, H. H.: *Elektrotechnische Zeitschrift*, 1954, 75, p. 763.

research is needed on this subject. To be complete, not only do transformer oil and its impurities need investigation, but also these in the presence of oil-impregnated paper. It is possible that the literature on cables and capacitors would repay examination.

The author has estimated from published experimental work the possible reduction in electric strength to be expected when oil is taken through the heating and cooling cycles in a sealed transformer. A colleague and I have obtained results in a single sequence of tests which agree fairly well with these estimations. Using the degassing equipment and test cell described previously,* we first filtered transformer oil under a partial vacuum so that the pressure of the gas in solution and of that in contact with the oil was 450 mm Hg. The subsequent sequence of pressures and electric strengths is shown in Table A, for a 2 mm gap which failed to

Table A

Pressure of gas in contact (p_4)	Pressure of gas in solution (p_g)	R.M.S. breakdown voltage Stainless-steel electrodes of ½in diameter	
		Gap of 2·00mm	Gap of 0·97mm
mm Hg	mm Hg	kV	kV
450	450	46	26
450	450	43	27
85	450	34	21
85	450	38	22
450	450	>46·5	28·5
85	450	36	—
760	760	>46·5	33
760	760	—	34·5

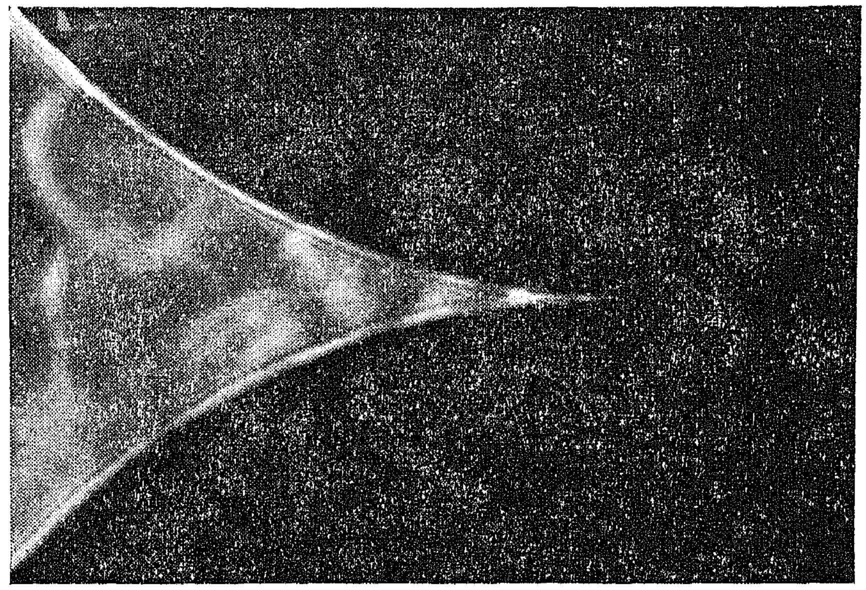
break down at atmospheric pressure owing to external flashover on the test cell, and for a 1 mm gap.

So far as they go, the corresponding results in the two tests agree. There was a pause of 10 min between breakdowns and 16 h was allowed for stabilization at atmospheric pressure. For the pressure conditions used by the author in Section 7 these results indicate a reduction in electric strength of 32% compared with his estimation of 35%. There are signs of conditioning* (a rise in strength during the first few breakdowns, probably caused by a process at the electrodes), so our value may be about 25%. Even this reduction, however, is serious enough to justify the author's conclusions, and I think that the percentage reduction would be higher for an oil of poorer quality.

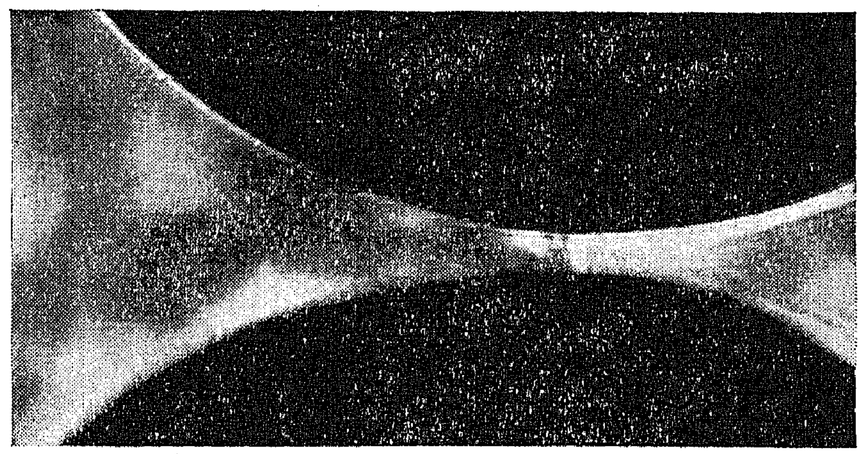
During the tests with excess pressure of gas in solution we observed bubble formation at field strengths below that for breakdown when some fibres present in the test cell happened to be in the gap. It is therefore probable that bubbles would be produced in a transformer, and owing to the possibility of their lodging in the windings, there could be a lowering of both the alternating and the impulse voltage strength.

Fig. B illustrates some of the work we are doing at Birmingham University, which I hope will solve many problems of liquid insulation failure. The photographic densities correspond to refractive index gradients and so to density and hydrostatic pressure gradients which result from the application of an electric field between the spherical electrodes. The turbulence effects, such as those shown, occur in a d.c. field well below that for breakdown in any but very clean and moisture-free liquids. Ultra-high-speed cinematography with high optical magnifications will permit the study of phenomena at the instant of breakdown.

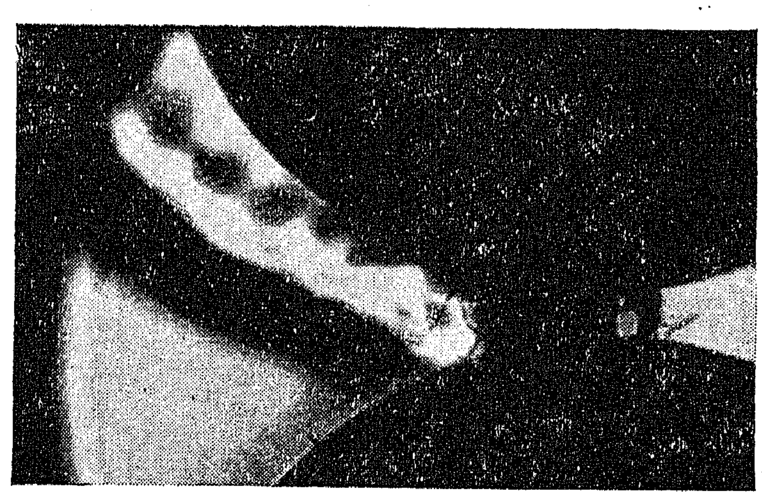
* WATSON, P. K., and HIGHAM, J. B.: "Electric Breakdown of Transformer Oil," *Proceedings I.E.E.*, Paper No. 1501 M, March, 1953 (100, Part IIA, p. 168).



(i)



(ii)



(iii)

Fig. B.—Schlieren photographs showing the effect of an electric field on an insulating liquid.

(i) Clean dry carbon tetrachloride during first half hour after a breakdown; turbulence disappears later.
(ii) Jet-like turbulence from a single moving fibre.
(iii) The effect with many stationary fibres.

Mr. Leslie Smith: Despite the author's contrary implication, the bellows arrangement or diaphragm has been used on transformers rated up to 750 kVA, and, with modification, up to 1 MVA; Fig. C shows a copper bellows of the type in question.

In Section 2 the author refers to the sealing of transformers of normal construction with an expansion space large enough to keep the pressure reasonable. I regard this as poor engineering practice, for I dislike a joint which needs to be airtight for successful operation and which cannot easily be tested. There are constructions which ensure that the main gasket is under oil (Fig. D), and with these it is possible for the joint to be tested

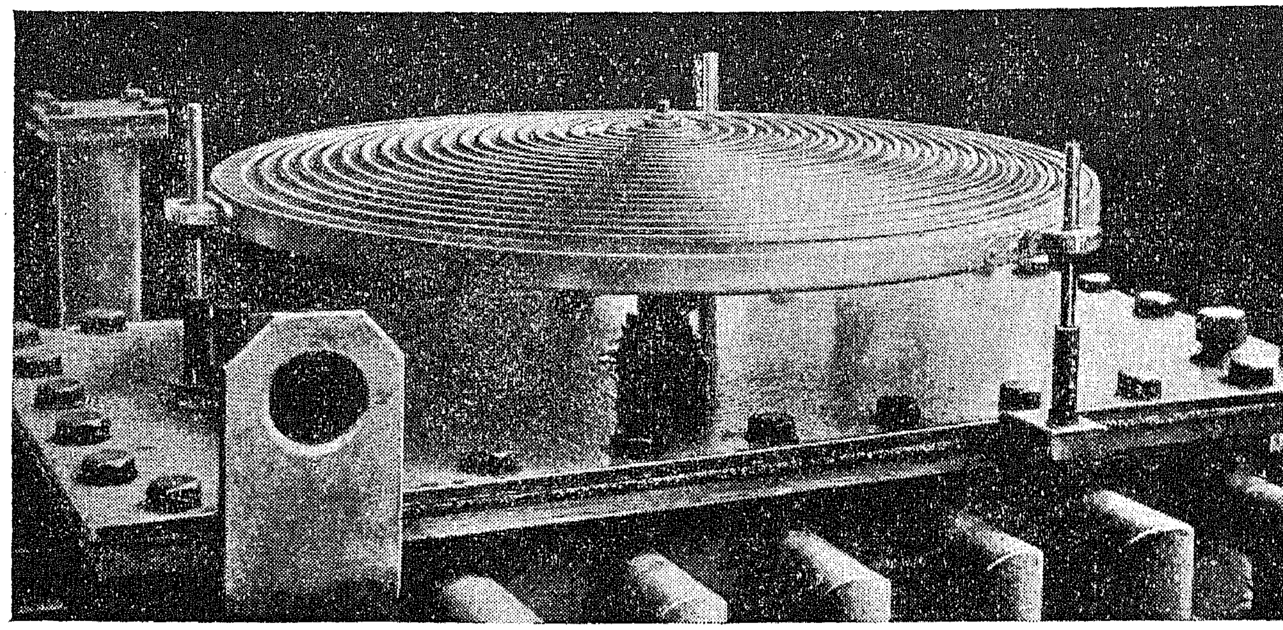


Fig. C.—Copper bellows for use up to 1 MVA.

under a considerable oil pressure, when leaks would be obvious. When such a test is carried out, and with the moderate negative pressures that develop inside the transformer when it is cooling, there is no danger of leakage of air inwards. The design and manufacturing procedures are so arranged that the pressures are in the range of $\pm$ 5 lb/in^2 without the use of spring-loaded valves.

In Section 8.1 the author refers to the practice of fitting low- and high-pressure valves, and I wonder whether this implies restricted breathing, which we all wish to avoid. Since we look to the sealed transformer for an obvious benefit—freedom from the need for frequent servicing—we should avoid valves or fittings in the air-space. Some 25 years ago I tried to use a small spring-loaded valve which was expected to operate at about 5 lb/in^2, and I believe that Mr. Welch's troubles with the old cushion-type transformer arose from an attempt to use a valve of that kind.

I think that the mechanism of such leakages involves a small orifice through which damp air leaks; once inside the transformer it expands, because of the negative pressure, and so deposits its moisture and initiates a train of events leading to the conditions to which Mr. Welch refers. This mechanism was probably responsible for the cupful of water I saw collected from the inside of a poorly constructed case. I have had experience over many years, however, of the cushion arrangement, where the case is high-pressure tested before sealing, and I have yet to find a transformer in other than first-class condition after a long period of service. The author rightly refers to the probable reduction in breakdown strength of oil at sub-normal pressures, but I believe that at moderate negative pressures and with generous designs the user need have no anxiety on this account.

I notice that throughout the illustrations the author has shown a maximum expansion space which is about 15% of the cold-oil volume, but in our practice we employ a very much larger space than that.

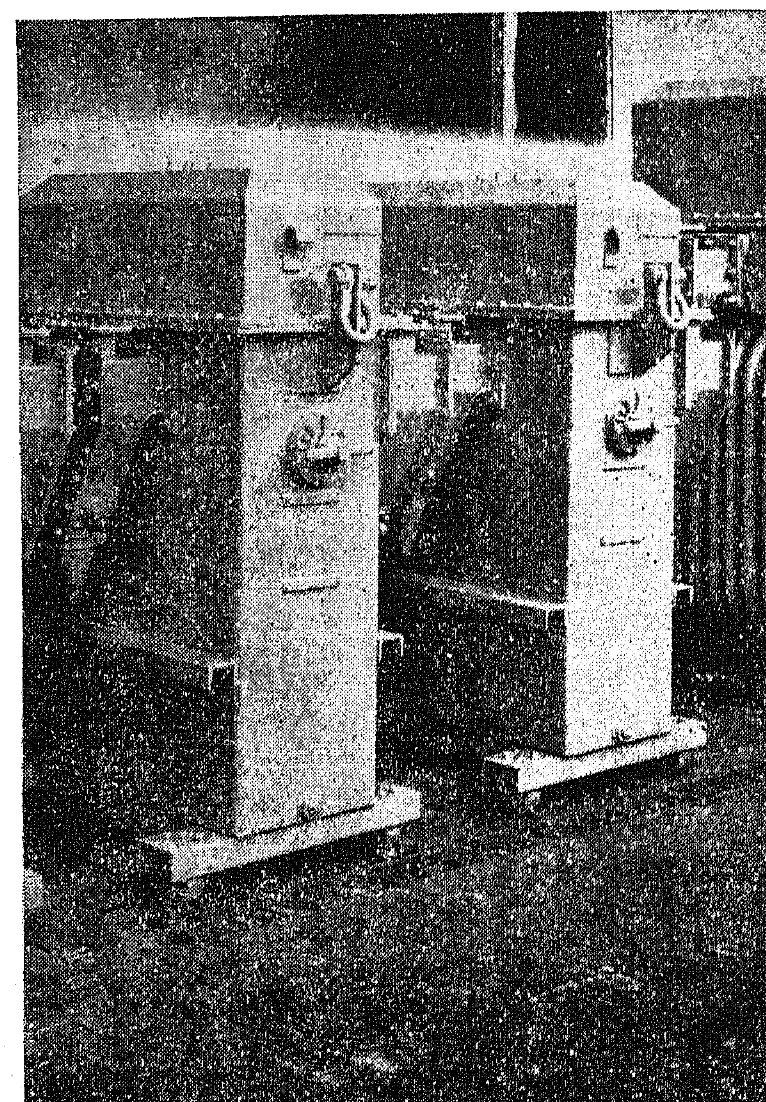


Fig. D.—Transformer sealed with gasket under oil.

Dr. A. L. Williams: I am surprised that transformer engineers still find it necessary to study a problem which cable engineers solved 30 years ago. I refer to the similarity between the transformer and the oil-filled cable, for the satisfactory life of both depends on complete filling with a good oil subsequently maintained in good condition. The latter can be achieved only by ensuring that gases and moistures are excluded so far as practicable, and by ensuring that the pressure never falls below atmospheric.

The method used in the cable is the first of the four described in Section 2, but it is dismissed as being confined only to small transformers. I can see no reason why it should not be used on transformers of any size, and, presumably, the larger the transformer the more important it is that it should be trouble-free. I appreciate that large oil volumes, with the necessity for cooling, present some engineering problems, but I should have thought the principle easier to apply to a transformer than to a cable. In the cable, severe transient and static pressures have to be dealt with in a long, flexible tubular construction, installed out of sight and out of reach, and the electrical and thermal conditions are onerous. In the transformer, on the other hand, one has to deal only with an accessible steel tank.

Apart from the question of construction, Section 7 refers to filling under 28 in of vacuum. To make a further comparison with cable practice, this is not a good enough vacuum to ensure

complete impregnation or to remove contaminating gases and moisture.

The results of these differences are apparent from the paper and the earlier discussion. Whereas the oil-filled cable is expected to live, and will live, for 30, 40 or 50 years without attention, in the case of the transformer, after a comparatively short period, one has to worry about acid value, interior rusting, sludge formation and deteriorating electrical quality. Even if the oil is changed, this does not remove harmful impurities entirely and does not prevent the cycle from starting all over again.

I should therefore like the author to explain what factors prevent the universal application of the only method of sealing which is technically sound.

Mr. J. H. Mason: Is there any practical justification for the author's suggestion in Section 7 that the infinite-time breakdown voltage at normal frequency may be about 73% of the 1 min breakdown voltage at twice normal frequency? My experience indicates that there is no simple correlation between the short-time and long-time electric strengths of insulation.

The long-time breakdown voltage is determined mainly by electrochemical effects in the oil and by discharges in the insulation. Above the discharge inception voltage the insulation is slowly degraded by the energy of the discharges and the life is proportional to the number of cycles of alternating voltage. The rate of deterioration increases rapidly with increasing voltage, as shown in Fig. E, which indicates that the ratio of the long- and short-time breakdown strengths varies for every type of insulation.*†

Recent investigation‡ shows that in short-time and step-by-step tests failure is due to the combined effects of stress concentration and local heating at the end of discharge channels. It is noteworthy that the step-by-step breakdown voltage of oil-immersed insulation is often increased when the breakdown strength of the oil is reduced by contamination or fibres, as shown in Table B.

Table B

THE EFFECT OF CONTAMINATION IN THE TEST MEDIUM ON THE STEP-BY-STEP ELECTRIC STRENGTH OF SHEET INSULATION

	Test medium			
	Clean B.30 transformer oil	Slightly contaminated oil	Oil contaminated after 50 tests on phenolic samples	Oil contaminated by sustained arcing through the oil
Breakdown voltage of oil, measured in B.S.I. test cell, kV(r.m.s.)	40	30	17	11
Polythene sheets 3·1 mm thick				
Number of tests	5	5	4	1
Breakdown strength measured with B.S.I. electrodes, kV/cm(r.m.s.)	117 ± 4	124 ± 3	134 ± 4	140
Phenolic impregnated paper sheets 3·2 mm thick				
Number of tests	3	—	—	2
Breakdown strength measured with B.S.I. electrodes, kV/cm(r.m.s.)	125 ± 8	—	—	164 ± 10

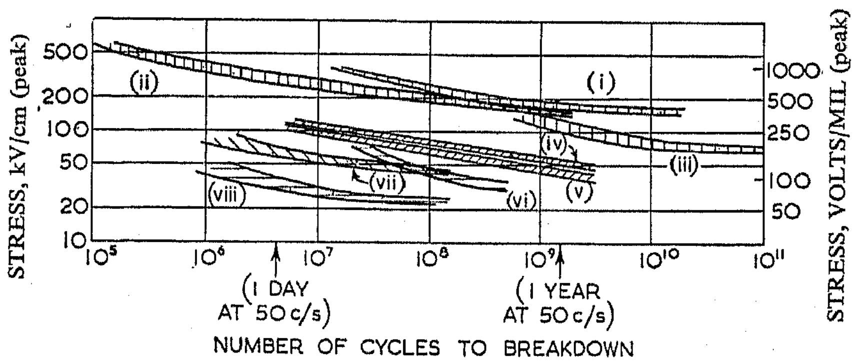


Fig. E.—Variation of the life of insulation with stress, in the presence of discharges.

(i), (ii) Polythene cables,* (i) U.R.32; $E_i \simeq$ 137 kV/cm (peak).
(ii) U.R.21; $E_i \simeq$ 100 kV/cm (peak).
(iii) Polythene discs with enclosed cavity, $\varepsilon = 2\cdot3$;
E_i between 35 and 50 kV/cm (peak).
(iv), (v) Polystyrene discs† with enclosed cavity, $\varepsilon = 2\cdot6$;
$E_i \simeq$ 28 kV/cm (peak).
(iv) Plasticized.
(v) Unplasticized.
(vi), (vii) Phenol formaldehyde with nylon and cellulose-filler,† $\varepsilon = 5\cdot6$;
$E_i \simeq$ 28 kV/cm (peak).
(vi) moulded cavity.
(vii) machined cavity.
(viii) Nylon discs with enclosed cavity;† $\varepsilon = 4\cdot0$, E_i = 20 kV/cm (peak).

In view of the rapid decrease in life of insulation with increasing alternating voltage, I would urge that d.c. or impulse tests, supplemented by a.c. discharge detection measurements should be substituted for a.c. over-voltage proof tests.

Mr. T. Williams: We are operating nitrogen-cushioned and air-sealed transformers both in service and under test conditions.

Two 50 kVA units under nitrogen are cyclically overloaded to effect an oil temperature of 90° C, and standard air-breathing units are run on the same cycle as a comparison. The oxygen in solution in the oil has fallen from 0·5% to 0·15–0·3% in two years and in the standard units it has risen to 1·5–2·0%. The acidity rose from 0·03 to 0·15 mg KOH/g, and we are of the opinion that nitrogen sealing is not justified in small units.

We have also operated for 18 months on commercial load 15 and 20 MVA units, each under a nitrogen cushion; in one case the oxygen in solution in the oil has fallen from 1·0% to 0·2%, and in the other from 1·5% to 0·2–0·3%. We have experienced considerable trouble on both units with leakage from gas-control equipment and one is virtually on hand control. In both cases, pressure is controlled between 1·5 and 5·0 lb/in².

Our third unit is a 7½ MVA 66/11 kV one operating under a simple air seal. Our problems have again arisen through leakage, although in this case in the transformer proper. In service, we have recorded a pressure range of from 3 in Hg positive to 5 in Hg

* HOWARD, P. R.: "The Effect of Electric Stress on the Life of Cables incorporating a Polythene Dielectric," *Proceedings I.E.E.*, Paper No. 1119, June, 1951 (98, Part 2, p. 365).

† PARKMAN, N.: "The Effects of Small Discharges on Some Insulating Materials," E.R.A. Report Ref. L/T321, 1954.

‡ MASON, J. H.: "Breakdown of Solid Dielectrics in Divergent Fields," E.R.A. Report Ref. L/T310, 1954.

negative, and on one occasion the Buchholz alarm operated through air entering the main tank. The analysis of gas collected gave a nitrogen/oxygen ratio of 8·4, and we believe that, had the gas resulted purely from liberation within the oil, the ratio would have been closer to that of the gas in solution, which was 18 at the conservator and 33 at the bottom of the tank. On test, air was observed bubbling in the Buchholz chamber at 5 in Hg negative pressure. Several attempts have been made to cure the leaks, but none appears to be completely successful. The unit has been resealed at an equivalent pressure of 2 lb/in^2 at conditions equal to 30 in Hg and 15° C, in order to maintain positive pressure, and so far, in spite of recent severe weather conditions, no negative pressures have been recorded and no gas has entered the float chamber.

In view of our experience, I believe that progress in the use of sealed transformers will require some adjustment to manufacturing technique, and manufacturers will be faced with the problem of constructing sealed units and designing efficient regulating valves.

In view of the general effect of gas solubility on the Buchholz device, the pressure to be considered is a change in absolute value, and as we have operated nitrogen-cushioned units with a pressure range comparable with that of the air-sealed unit without trouble, I feel that within reasonable limits this form of protection may still be used.

I understand that gas goes into solution more readily than it will come out, and I thus wonder whether a supersaturated state can exist and where the gas is liberated when the pressure falls. If it occurs mainly on the free surface, namely in the conservator tank, the Buchholz protection would remain unaffected. I am not unduly worried by the dielectric effect of the electrical stress on the oil at the voltages under consideration, but I wonder how it affects gas liberation. Does its presence promote liberation or not?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. E. B. Franklin (*in reply*): I endeavoured to avoid passing opinion on the relative merits of sealed transformers; type (*d*) is simple in construction, but certain problems associated with it did not seem to have been exposed in the past and the paper is foremost a preliminary examination of these problems.

Mr. Welch's unfortunate experience is probably the result of faulty design in which the solution of gas in oil had not been accounted for correctly. However, sealed-transformer performance cannot be judged from such faulty units and the principle thus condemned.

Low working temperatures (with uneconomic utilization of active material) may contribute in no small way to the satisfaction expressed with conventional breather types.

On the subject of electric strength, one cannot unfortunately summarily dismiss the lowering of electric strength under certain conditions if the full implication of this with attendant bubble formation is grasped.

Mr. Richards and Mr. Smith raise the question of gasket joints, indicating that a joint under oil is infinitely better than a joint in air. This may be a false assumption when entry of air from outside under negative pressure is considered; joints tight to oil are not necessarily tight to air.

I feel that the complication of valves is better avoided if possible, but I do not agree that reliable correctly regulated valves give rise to restricted breathing. For example, after filling with degassed oil, pressure stabilization would come about with one or two valve actions, but after this further operation would not normally occur.

Mr. Thompson has drawn attention to the difference that may exist between oxygen quantities required to produce given acidity values under limited and free oxygen-access conditions in the laboratory. However, the statement making reference to dangerous generalization is rather unjustified and is misrepresentative of fact. Field experience is more convincing as final evidence than laboratory test. The fact is that air-sealed transformers have been extensively used in the past and are shown to limit oxygen access to values such that troublesome oil deterioration is eliminated. I cannot make economic comparisons between sealed types and conventional types using inhibited oil. However, it is interesting to note that the former has an advantage in that more simple protection against humidity is offered, which is of great importance.

Mr. Chadwick has provided extremely useful and interesting information on the subject of Buchholz operation and the release of bubbles under electric stress. From this there are obviously as yet unsolved problems connected with this type of transformer. The curves show remarkable sensitivity of the bubble-release stress to excess pressure of gas in solution.

Commenting on Dr. Highams's experiments, it is probably the figures before conditioning that are of interest with sealed transformers.

Dr. Williams has quite rightly pointed out that what the transformer engineer has been content with is not at all good enough for cable engineers. The fact is that some transformer engineers are only now beginning to realize that the treatment of a high-voltage transformer should assume the same importance as the treatment of cables. There are engineering difficulties involved in the sealing of large transformers in the manner suggested, because of the large oil quantities and the extreme temperature variations.

In reply to Mr. Mason, the 73% quoted in Section 7 is taken from Montsinger's work.* The simple relationship was taken to illustrate the importance of a large additional drop in electric strength after works test. Where composite insulation is involved, the problem is obviously more complex than indicated, and here again research is necessary to determine how oil-impregnated insulation behaves when the oil becomes super saturated with gas in solution. Preliminary tests made some time ago showed that the dependence of breakdown on applied pressures and gas in solution was greater with fibre-contaminated oil.

Mr. Williams wonders whether gas can be liberated from supersaturated oil in regions where Buchholz operation would result. I believe that under certain conditions the bulk of gas slowly liberated would be below the main cover and would thus operate the Buchholz relay. If the pressure due only to the head of oil acting, say, at cover level were greater than the excess pressure of gas in solution, gas liberation would not be likely below this level. Mr. Chadwick's curves provide the answer to the last question posed by Mr. Williams.

* MONTSINGER, V. M.: "Effect of Time and Frequency on Insulation Tests on Transformers," *Transactions of the American I.E.E.*, 1924, 43, p. 337.

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Paper No. 1706 S
Sept. 1954

THE ECONOMIC SELECTION OF COOLING TOWERS FOR GENERATING STATIONS

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(*The paper was first received* 3rd *February, and in revised form* 28*th May*, 1954. *It was published in September*, 1954, *and was read before the* Supply Section 5*th January, and the* Mersey and North Wales Centre 10*th January*, 1955.)

SUMMARY

The paper describes the construction of charts showing the economic duty conditions of natural- and mechanical-draught cooling towers for generating stations in the British climate. The charts are drawn in terms of two factors, namely (*a*) the annual station load-factor, and (*b*) the full-load turbine heat-rejection per square foot of net exhaust area. Typical seasonal temperature and load cycles are assumed.

The calculations indicate that past design practice often led to towers which were unduly large and water-temperature ranges which were unduly small. By correct design, net capitalized savings of the order of £200 000 per 240-MW station can be made in some instances. The advent of larger turbine units and the associated higher values of factor (*b*) will make higher water temperatures economic.

With mechanical-draught towers, the water temperatures specified should generally be lower than with natural-draught units. A chart is constructed showing the difference in the overall costs of generation of stations fitted with natural and mechanical-draught towers. This chart suggests that mechanical-draught towers are economic only at low values of factor (*b*), such as those obtained on small turbines. Another chart shows the effect of varying climatic conditions on the comparison. Higher air temperatures favour mechanical draught.

Circuits for combined river and cooling-tower schemes are examined. With these arrangements the cooling towers generally operate mainly during the summer season, and consequently mechanical-draught towers are often economic. Even with small rivers having widely variable discharges, such combined schemes can be responsible for substantial savings relative to pure cooling-tower schemes.

(1) INTRODUCTION

The designer of inland power stations is faced with a number of problems concerning the economic disposal of the heat of condensation. Often a choice exists between a "straight" cooling-tower installation and one co-ordinated with a small local river: there is also a choice between cooling towers of the natural- and mechanical-draught types. Whichever type is selected, the economic duty conditions have to be found for the purpose of the cooling-tower specification. An incorrect decision on any of these issues can result in substantial additional costs of generation.

The paper shows how these issues can be decided and, more specifically, presents the economic solutions in graphical form over the range of conditions met in British stations.

The treatment also involves a discussion of the economic duties of the other components of the heat-rejection circuit shown in Fig. 1, i.e. the condenser, circulating-water plant and turbine exhaust.

(2) PROCEDURE FOR DETERMINING ECONOMIC DUTY CONDITIONS

The basic procedure for determining the economic duty of a cooling tower is well known. It consists in determining

(*a*) The additional annual investment in the cooling tower required to give a specific improvement in performance, e.g. a reduction in the inlet and outlet water temperatures by 1°F at specified atmospheric and heat-load conditions.

(*b*) The financial value of the improvement in performance to the generation authority, i.e. the value of the additional electricity

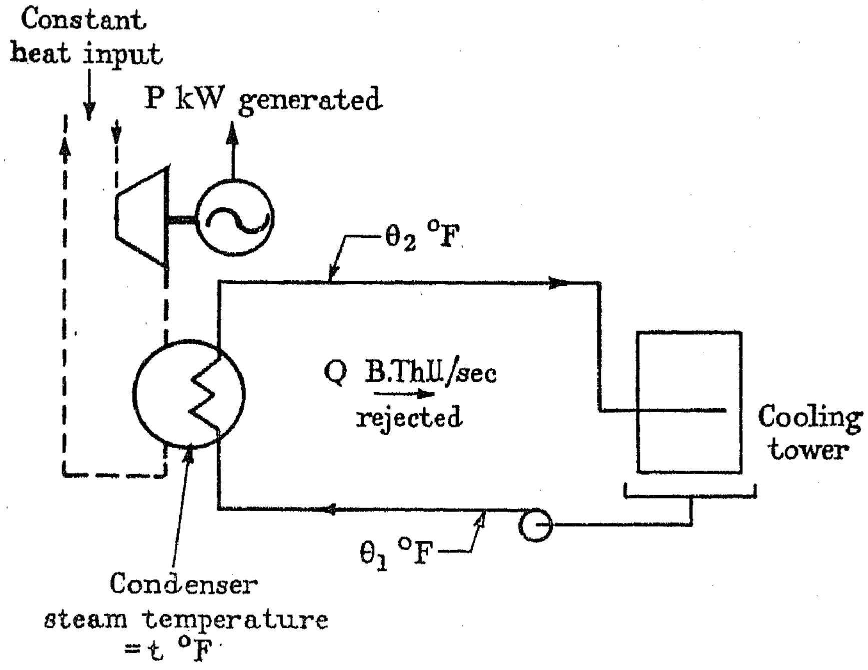


Fig. 1.—Generating-station cooling circuit.

$$(\theta_1 + \theta_2)/2 = \theta_m$$

which can be generated for the same station heat intake, less any increase in the cost of primary plant items such as the turbo-generators.

The economic duty point is that for which (*a*) is equal to (*b*). If desired, a profit allowance can be included in the capital charge rate in establishing this equality.

The additional investment (*a*) is easy to calculate now that reliable performance and cost data for cooling towers are available. The calculations in the paper are based on performance equations of the type proposed by Chilton,[1] and generalized by Margen[2] to apply also to mechanical-draught towers. The cost data are described in Section 10.1.1.

The additional financial value, (*b*), involves three primary variables, namely

(i) The station loading programme in various seasons.
(ii) The ratio of the full-load heat rejection, Q_{FL}, to the net area of the turbine exhaust. This ratio will be termed the "turbine-exhaust heat loading," q_e.
(iii) The condenser steam temperature, *t*.

In Britain, most generating stations which have a given annual load-factor, also have fairly similar load programmes. It is considered that these programmes are represented with sufficient accuracy for the purpose of the paper by load-allocation diagrams of the type shown in Fig. 2. Having drawn one load-

Mr. Kennedy is with Kennedy and Donkin.
Mr. Margen, formerly with Kennedy and Donkin, is now with Aktiebolaget Atomenergi, Stockholm.

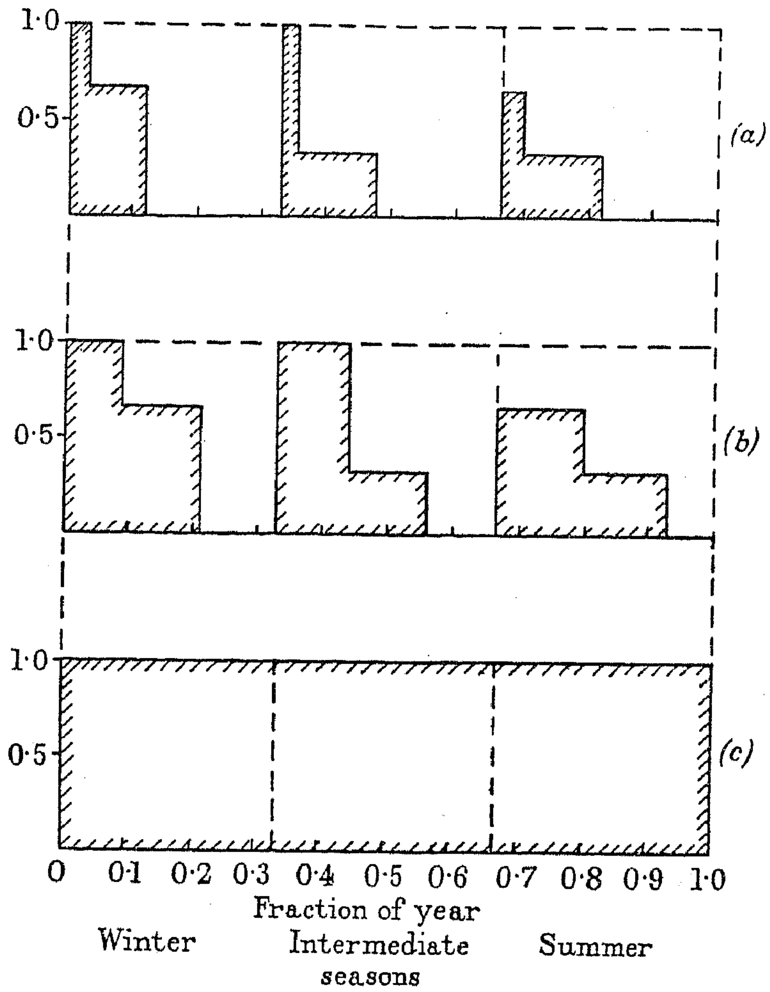


Fig. 2.—Seasonal block-load allocation diagrams used in calculations.
(a) 20% annual load factor.
(b) 45% annual load factor.
(c) 100% annual load factor.

allocation programme for each load factor, variable (i) may then be represented by load factor only.

Variables (ii) and (iii) influence the result because an increase in the turbine-exhaust heat loading or reduction in the condenser steam temperature increase the turbine leaving loss. The higher the leaving loss, the lower is the net benefit obtained

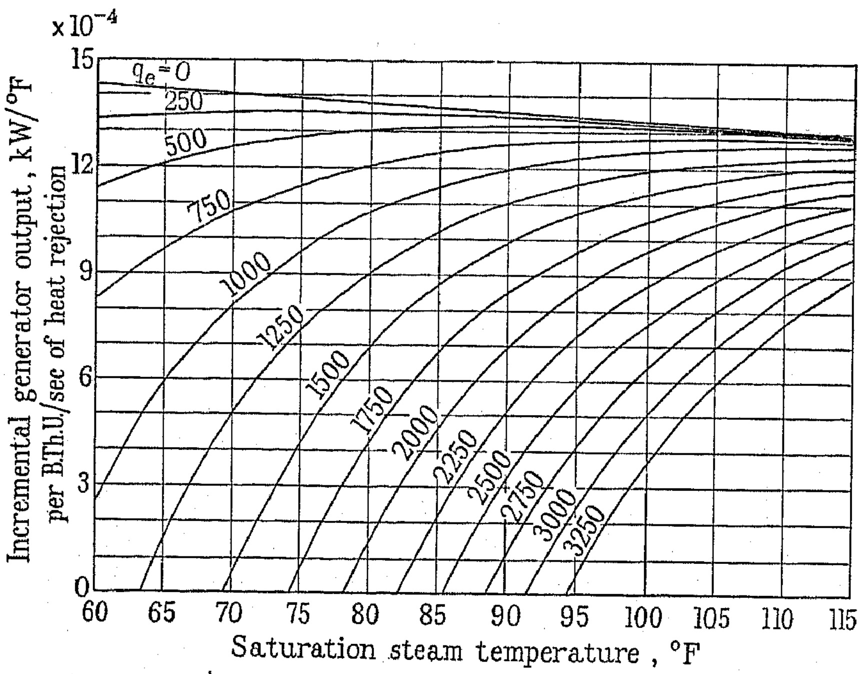


Fig. 3.—Incremental generator output per degree Fahrenheit in condenser steam temperature (based on $\eta_t = 0 \cdot 7$).

from reducing the condenser steam temperature. This is brought out clearly in Fig. 3.

Variable (ii), i.e. the turbine-exhaust heat loading, is a design constant of the turbine which can vary over a wide range, being in general small with turbines of low rating, and large with turbines of high rating, unless a large number of exhausts are used. Typical figures are given in Table 1.

Table 1

TYPICAL EXHAUST HEAT LOADINGS FOR TWIN-FLOW TURBINES

Turbine rating	Exhaust heat loading (q_e)
MW	B.Th.U./sec-ft²
30	1 100
60	1 500
100	1 900

Variable (iii), i.e. the condenser steam temperature, depends largely on atmospheric conditions. Throughout the British Isles these may be represented approximately by dividing the year into three seasons of equal duration which have the effective mean wet- and dry-bulb temperatures shown in Table 2. The condenser steam temperature is also dependent on the particulars of the cooling tower, condenser and circulating-water plant. When a designer sets out to find an economic heat-rejection circuit for a new station, these plant particulars are initially unknown. Their economic values must therefore be determined simultaneously* by trial methods.

Table 2

ASSUMED MEAN ATMOSPHERIC TEMPERATURES

Season	Temperature	
	Wet bulb	Dry bulb
	°F	°F
Winter	41	43
Intermediate	49	52
Summer	57	61

The above discussion suggests that there are only two independent variables of major consequence for British generating stations relying entirely on cooling towers, namely the annual station load-factor, L, and the full-load turbine-exhaust heat loading, q_e. The economic duty of heat-rejection plant may then be represented by plotting the following three parameters on charts having L and q_e as co-ordinates:

(a) The economic full-load cooling-tower temperature difference, $(\theta_m - t_{w1})$, where θ_m is the algebraic mean of the inlet and outlet circulating-water temperatures, and t_{w1} is the atmospheric wet-bulb temperature.

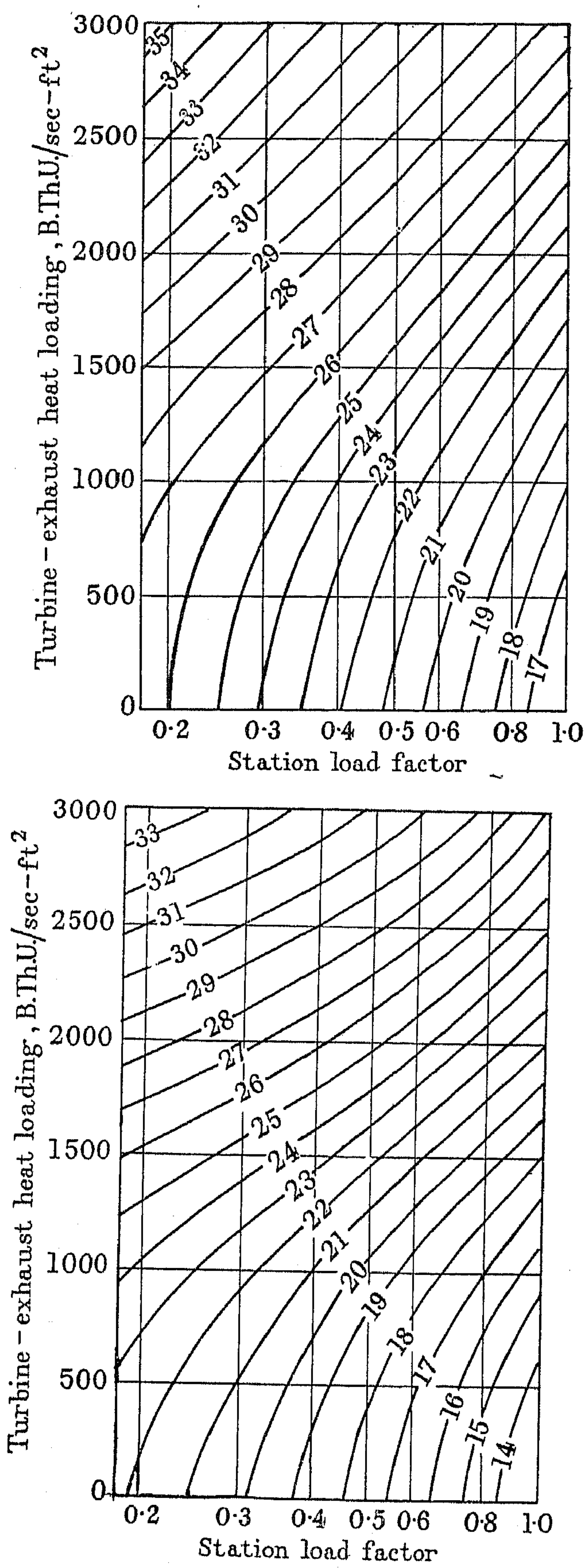
(b) The economic full-load condenser temperature difference, $(t - \theta_m)$, where t is the steam temperature in the condenser.

(c) The economic full-load temperature range, $(\theta_2 - \theta_1)$, of the circulating water (which is an inverse measure of the water quantity).

The values of the first of these parameters are shown in Figs. 4(a) and 4(b) for natural- and mechanical-draught towers

* This finding conflicts with a conclusion reached by Bottomley[1] in 1941 by an interesting but oversimplified method. He assumed that the improvement in turbo-generator performance per degree Fahrenheit of water-temperature reduction was constant, and consequently concluded that the economic cooling-tower size, condenser size and circulating-water quantity were independent of one another. Fig. 3 indicates that Bottomley's assumptions would not be seriously in error for very small turbines which might have values of q_e below 750 B.Th.U./sec-ft², but that it would be quite unjustified for the values of q_e used in large modern turbines.

respectively,* and the values of the second and third parameters are shown in Fig. 5.



(a)

(b)

Fig. 4.—Economic mean temperature difference of cooling towers.

The curves show the temperature difference ($\theta_m - t_{w1}$) to be specified at the reference conditions of atmospheric temperatures: wet bulb = 49° F; dry bulb = 52° F.

(a) Natural draught.
(b) Mechanical draught.

* Figs. 4(a) and 4(b) give the tower performance at the following atmospheric reference temperatures: wet bulb, 49° F; dry bulb, 52° F. To obtain tower performance at other atmospheric conditions, proceed as follows:

(a) From reference value of ($\theta_m - t_{w1}$) and reference atmospheric wet-bulb temperature read off the reference "enthalpy difference" designated by ($h'' - h_1$) in Fig. 2 of Reference 4.

(b) Read off atmospheric factors y_M (for mechanical draught) or y_N (for natural draught) from Fig. 1 of Reference 4 (for the new atmospheric conditions), and multiply the reference enthalpy difference by $y_M/1\cdot42$ or $y_N/10\cdot23$ to obtain the new enthalpy difference.

(c) For the new enthalpy difference and the new atmospheric wet-bulb temperature read off the new value of ($\theta_m - t_{w1}$) from Fig. 2 of Reference 4.

Step (b) can usually be omitted for mechanical-draught towers, since $y_M/1\cdot42$ is usually close to unity. Steps (a) and (c) can be performed from standard hygrometric tables if Reference 4 is not available. (See definitions in Section 10.)

(3) DISCUSSION OF ECONOMIC DUTY CONDITIONS

Figs. 4(a) and 4(b) show clearly the very large effect of the turbine-exhaust heat loading on the economic water temperatures. As larger turbine units come into use, the exhaust area cannot keep pace with the increase in the quantity of heat rejected per machine, so that inevitably the turbine-exhaust heat loadings gradually increase and higher water temperatures, i.e. less exacting cooling-tower duties become economic. Load factor also has a fairly pronounced influence on the economic water temperatures, an increase in load factor producing a reduction in the economic water temperatures. The economic water temperatures for mechanical-draught towers are lower than those for natural-draught units (over the relevant range of duty conditions) so that, where tenders for both types are desired, different performance specifications should be formulated.

The charts are based on towers with splash-bar packings, and 3–8% should be added to the values of ($\theta_m - t_{w1}$) for application to film-type packing designs.

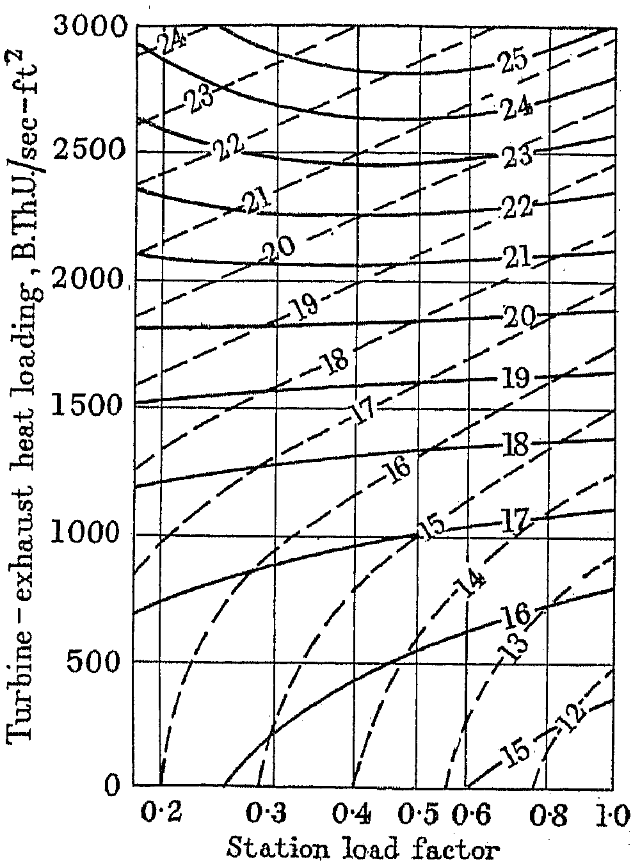


Fig. 5.—Economic water-temperature range and condenser-temperature difference.

——— Water-temperature range, ($\theta_2 - \theta_1$), °F.
- - - - - Algebraic mean temperature difference across condenser ($t - \theta_m$), °F.

The curves are calculated for natural-draught cooling towers, but apply to mechanical-draught towers within ±1° F.

The full lines on Fig. 5 indicate that load factor has relatively little effect on the economic temperature range of the water, whereas the exhaust heat loading has a very pronounced effect. The charts suggest that the economic temperature ranges are higher than those which have been used in the past, when temperature ranges as low as 12°F were often used. This practice probably sprang from the incorrect application of designs developed for river stations to cooling-tower applications. Table 3 compares the calculated economic temperature ranges for the two types of station.

Regarding the calculated economic temperature differences across the condenser represented by the broken lines in Fig. 5, it is necessary to make the reservation that cost relations for condensers are more variable than those for cooling towers, particularly because the condenser dimensions may influence the dimensions and costs of the power-station buildings. The condenser relations used in the paper are, however, considered to

Table 3

COMPARISON OF ECONOMIC CONDENSER AND CIRCULATING-WATER DESIGN FOR TYPICAL RIVER AND COOLING-TOWER STATIONS

($L = 0{\cdot}45$, $q_e = 1\,250$ B.Th.U./sec-ft^2)

Item	Station	
	River	Cooling tower
Economic water-temperature range, $(\theta_2 - \theta_1)$, °F	13·3	17·7
Economic condenser temperature difference, $(t - \theta_m)$, °F	17·5	16·0

be sufficiently representative for the main object of the paper, i.e. the presentation of charts giving realistic assessments of economic cooling-tower duty conditions. For this purpose a high degree of accuracy of assessing the economic condenser performance is not necessary. The values shown in Fig. 5 incorporate an allowance for deterioration in service due to scale deposit.

Table 4

COST COMPARISON OF TWO COOLING-TOWER SCHEMES FOR 240-MW STATION

($L = 0{\cdot}45$, $q_e = 1\,500$ B.Th.U./sec-ft^2)

Item	Original design	New design
Design conditions based on atmospheric reference conditions of 49°F *wet bulb,* 52°F *dry bulb:*		
Cooling-tower temperature difference $(\theta_m - t_{w1})$, °F	22·7	25·6
Water temperature range, $(\theta_2 - \theta_1)$, °F ..	12	18·6
Condenser temperature difference* $(t - \theta_m)$, °F	13·5	16·8
Full-load station heat rejection, B.Th.U./sec	400 000	400 000
Annual costs:		
Capital charges and maintenance on towers, £/annum	56 400	44 400
Circulating-water pumping costs, £/annum ..	48 500	28 600
Difference in charges on piping, culverts, valves, etc., £/annum	7 000	—
Effect of difference in vacuum, £/annum ..	—	22 000
Total	111 900	95 000
Saving in favour of new design, £/annum ..	—	16 900
Saving capitalized at 7·7%, £/annum ..	—	219 000

* This corresponds to a terminal temperature difference of 7·5°F at the hot end of the condenser for either design. Assuming that the water velocities for the two designs are in the ratio 1·55 : 1, the same condenser can be used for either scheme. See Section 10.4.2 for description of other assumptions.

Table 4 illustrates the importance of specifying the cooling tower conditions in accordance with the above discussion. The first column is a typical example of a station designed some years ago, when there was a tendency to make towers large to reduce carry-over of water drops, and a tendency to adopt too low water temperature ranges. The second column shows corresponding costs with towers designed to an economic specification, and indicates that this would result in a net capitalized saving of over £200 000 for a 240-MW station. As several stations laid down some years ago with such over-generous cooling towers are now only partially constructed, the opportunity still exists to improve the design by omitting one tower and several pumps. It should be pointed out that part of this improvement has been made possible only by the development of satisfactory "eliminators" by the British Electricity Authority,[2] which reduce carry-over to negligible amounts even when the cooling towers are small in relation to the heat quantity.

(4) NATURAL VERSUS MECHANICAL DRAUGHT

Fig. 6 shows the comparison of the total annual costs of natural- and mechanical-draught towers, the area below the

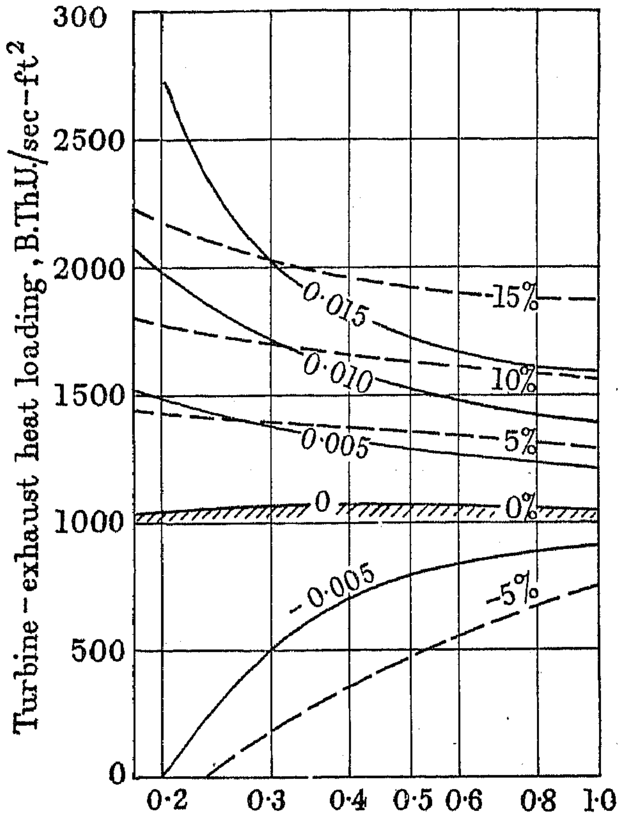


Fig. 6.—Economic comparison of natural- and mechanical-draught towers for British stations.

The curves show the total costs of generation with mechanical-draught towers less the total costs of generation with natural-draught towers.
——— £ per annum per B.Th.U./sec of full-load heat rejection.
- - - - - Percentage of economic capital charges on natural-draught towers.

heavy shaded line representing the range of conditions over which mechanical-draught towers are estimated to be financially superior to natural-draught towers. The other curves on the chart show the net difference in the annual costs expressed in pounds per annum per British thermal unit per second of the full-load heat rejection. A difference of 0·01, for instance, represents £1 000 per annum for a 60-MW set. The chart should not be used as a firm basis of selection between natural- and mechanical-draught towers, because site conditions affect the relative prices to some extent, and makers' quotations are not always offered on the same basis. Nevertheless, the chart gives a good indication of the main factors which influence the financial comparison.

(4.1) Influence of Turbine-Exhaust Heat Loading

Inspection of the chart indicates that the exhaust heat loading has a very strong bearing on the comparison, a high heat loading favouring natural draught. To explain this, one may regard a natural-draught chimney as an engine which develops useful air power in proportion to its height and the amount of heat supplied to it. The heat is a waste product, so that the chimney is economic if the power developed from this free heat is sufficient to pay for the capital charges. Now the discussion in Section 3 has shown that an increase in the turbine-exhaust heat loading produces an increase in the economic water temperatures, and hence a reduction in the economic ground area of the chimney.

In other words, the chimney can still develop the same air power but costs less to construct and is consequently more economic. Hence high turbine-exhaust heat loadings are advantageous to natural draught.

(4.2) Influence of Load Factor

Fig. 6 also shows that, contrary to common belief, the station load factor has little influence on the economic comparison between natural- and mechanical-draught towers. The prevalent belief that natural-draught towers tend to be more economic at high than at low load factors is probably based on the supposition that a chimney developing free air power continuously is in a better position to pay for its capital charges than one which develops power for only a small fraction of the year. That argument is correct in itself, but there are other factors which cancel its effect. The most important of these is the fact that with higher load factors larger towers (i.e. chimneys with larger ground areas) are economic, as shown in Section 3. Hence the cost of the chimney also increases. Furthermore, for a given heat quantity supplied to it, a cooling-tower chimney can develop more power on cold days than on hot days. Low- and medium-load-factor stations tend to have more of their operating time in the winter than in the summer, and from that aspect are favourable to natural draught. Stations with very high load factors (i.e. approaching 100%) must inevitably be loaded almost as heavily in summer as in winter. Fig. 6 shows that the various factors mentioned above approximately cancel, i.e. that station load factor has little influence on the economic comparison.

(4.3) Influence of Climate

Fig. 7 shows the dividing lines between the economic spheres of application of mechanical- and natural-draught towers for various climatic conditions. Each curve is based on one wet-bulb temperature and an associated dry-bulb temperature, which are assumed to be maintained throughout the year. Moreover, to simplify the calculations for this chart, it is assumed that the towers are never on partial load, so that a load factor of 40% is, for instance, obtained by operating the tower on full load for 40% of the year.

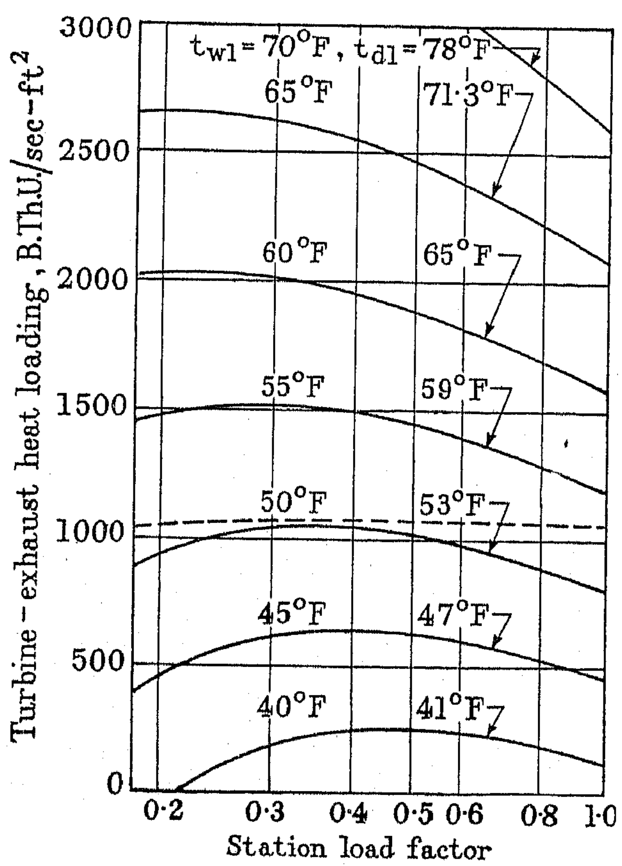


Fig. 7.—Influence of climate on relative merits of natural- and mechanical-draught towers.

The curves show the conditions under which both towers give the same overall cost of generation, natural-draught towers being economic above the curve.

- - - - - British conditions (from Fig. 6).

The Figure shows the very pronounced influence of the climate. With a mean wet-bulb temperature of 40° F there is no economic application at all for mechanical-draught towers, however low the exhaust heat loading; for a mean wet-bulb temperature above 70°F there is no economic application for natural-draught towers, for any foreseeable turbine exhaust heat loading. Northern Canada and India are examples of these two extreme conditions. The United States has average air temperatures more than 10°F higher than Britain, and this in itself would explain the predominance of mechanical-draught towers in American power stations and the predominance of natural-draught towers in British ones. The precise positions of the dividing lines on Fig. 7, of course, depend on the cost data capital-charge rates, and modified data may apply in countries other than Britain.

With the uniform load and temperature conditions assumed for each curve in Fig. 7, the station load factor does influence the economic comparison between natural and mechanical draught towers to a small extent.

(5) ECONOMIC OPERATION

With natural-draught towers fitted with water-distribution systems which work effectively over a wide range of water quantities, it does not pay to shut down some of the towers, however light the station heat load. The only independent operating variable is thus the water quantity, and this should be reduced by reducing the number of pumps on load whenever the incremental generator output (plotted in Fig. 3) reaches a low value, i.e. whenever a greater economy can be obtained by reducing the pumping power than by improving the vacuum. This reduction in the number of pumps on load should take place particularly in the winter and at times of low station load.

With mechanical-draught towers it does pay to cut out some of the tower cells at times of light station load or low atmospheric temperatures in order to reduce the power consumption of the fan. Fig. 8 shows the load below which cutting out of cells should start in various seasons. In practice, it is doubtful whether operation would always conform precisely with the most economic programme, and for that reason it was assumed in

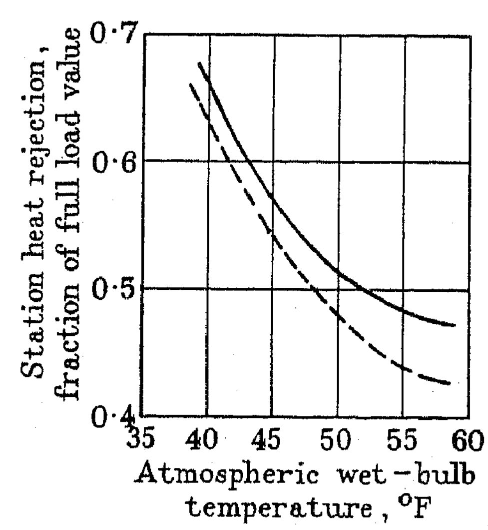


Fig. 8.—Mechanical-draught tower operation.

The curves show the highest heat load at which it is economic to maintain all cells in operation.

——— Based on simplified performance relation, eqn. (1*a*).

- - - - - Based on estimated actual performance.

the calculations that cells would be cut out whenever the load fell below one-half of full load.

Calculations for the paper are based on single-speed motors, but for certain ranges of conditions the extra expense of two-speed or even variable-speed motors is justified by the reduction in the average power consumption by the fan. The net change in the overall annual costs, however, is not sufficient to change Figs. 6 and 7 appreciably.

(6) COMBINED RIVER AND COOLING-TOWER SCHEMES

Where a direct choice exists between the use of a self-contained river cooling scheme and a cooling-tower scheme the former would almost invariably be chosen, because the river works usually cost much less than the cooling towers, the average vacuum obtained by river cooling is better and the pumping costs are lower. Altogether these factors may account for a capitalized saving of some £800 000 for a 240-MW station.

There are, however, few rivers in Great Britain large enough to deal with the entire heat rejection of modern generating stations during especially dry periods. More often, combined river and cooling-tower schemes have to be adopted, and these can be arranged in two basic types of circuit, shown in Fig. 9. Circuit (*a*)

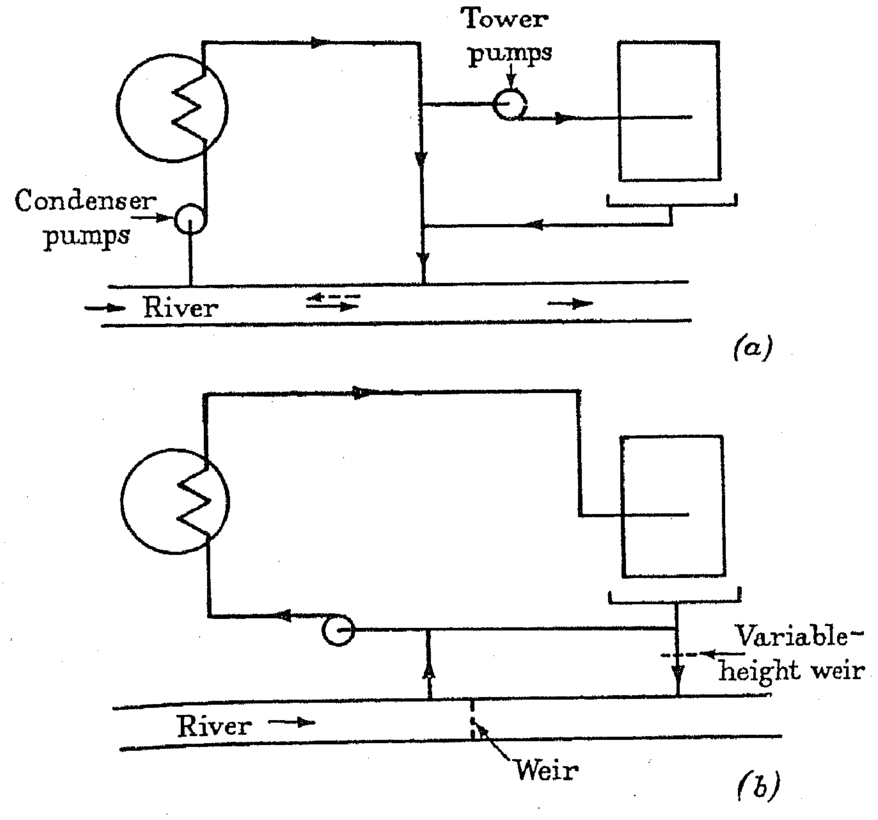


Fig. 9.—Cooling circuits for combined river and tower scheme.

(*a*) Circuit with "shunt" across towers; flow direction reverses during very low river discharges.
(*b*) Simple series circuit; modified arrangements without weirs are possible.

has a shunt across the towers which enables the station to operate normally with river cooling, the tower being brought into operation only at times of low river discharge to prevent the river temperature from rising to unacceptable values. The provision of separate condenser and cooling-tower pumps minimizes pumping costs, since most of the water is pumped only against the friction head in the condenser circuits, and not the static head of the tower circuit. Variable-speed motors may be used for the cooling-tower pumps to facilitate river-temperature control. With fairly large rivers the tower would normally be used mainly in the summer, i.e. the season of low river discharges and high river temperatures, and in these circumstances mechanical-draught towers would generally be economic. Table 5 gives leading particulars of such a scheme, where the river can absorb only 16% of the full-load station heat rejection

Table 5

COMPARISON OF HYPOTHETICAL COMBINED RIVER AND COOLING-TOWER SCHEME WITH NORMAL COOLING-TOWER SCHEME

($L = 0{\cdot}45$, $q_e = 1\ 500$ B.Th.U./sec-ft^2)

Assumed permissible heat rejection to river per unit full-load station heat rejection.*	
Winter	0·9–1·6
Spring and autumn	0·375–0·6
Summer	0·165–0·34
Annual mean	0·61
Minimum	0·165
Full-load station heat rejection	400 000 B.Th.U./sec
Nominal tower rating	
Type of tower	Mechanical draught
Rated heat load	200 000 B.Th.U./sec
Rated temperature difference at reference atmospheric conditions	27·5°F
Reductions in costs relative to normal cooling-tower scheme†	£/annum
Cooling tower costs (capital charges, maintenance and fan power)	26 300
Pumping costs (including capital charges and maintenance)	14 550
Effect of vacuum on operating costs	13 620
River works, piping, culverts	−12 000
Total reduction	£42 470
Total reduction in annual costs capitalized at 7·7%	£550 000

* For detailed particulars see Table 9.
† Scheme as shown in Table 4.

in the driest period of the year, but is estimated to save a capitalized amount of £550 000 for a 240-MW station.

The simple series arrangement, shown in Fig. 9(*b*), should be used with smaller rivers, which make only a minor contribution to the cooling process and consequently do not warrant the provision of two stages of pumps. In this case the pumping power is not much less than for a pure cooling-tower station, but there remains the reduction in the capital cost of the towers and the improvement in the average vacuum.

In the past a common fault has been the selection of towers as large as those which would be employed for a pure cooling-tower station; by this means much of the potential saving which can be derived from using river water for cooling is sacrificed.

It will be understood from Table 5 that the financial value of utilizing rivers in correctly designed combined schemes can be very large. The main obstacle to the wider use of rivers in such schemes appears to be the absence of a clear policy to govern the permissible amount of heat rejection to rivers. It is probable that an investigation would indicate that most rivers could absorb heat without significant disturbance to public and private interests provided the river temperature rise, or the actual river temperature attained, was kept below certain limits. The importance of the subject appears to call for such an investigation on a national scale.

(7) CONCLUSIONS

The charts presented in the paper show the economic cooling-tower duty conditions for all British generating stations relying solely on towers with an accuracy sufficient for practical purposes. By their use in formulating cooling-tower specifications, substantial savings can be made relative to designs based on past practice. In particular, there has been a tendency to employ unduly large towers and to specify unduly small water-temperature ranges.

Cooling-tower duty conditions will become less onerous as larger turbine units with inevitably larger exhaust heat loadings

come into general use. This trend of development will strengthen the financial advantage of the natural-draught tower over mechanical-draught units for British stations. It is only in combined river and tower schemes or in hotter climates that the mechanical-draught tower becomes economic for generating-station appliances.

The use of local rivers for supplementary cooling should always be investigated, since large savings often result. With relatively large rivers a circuit should be adopted which avoids pumping all the water against the static head of the towers. There appears to be a strong case for conducting a national investigation into the amount of heat which can be rejected to British rivers without interfering unreasonably with public or private interests.

(8) ACKNOWLEDGMENTS

The authors are indebted to the North Western Division of the British Electricity Authority for permission to carry out tests on cooling towers at Hartshead generating station to assess the effect of varying water-temperature range on cooling-tower performance. They wish to thank the Manchester staff of Kennedy and Donkin for carrying out these tests, and Mr. J. R. Bond, Station Superintendent, and his staff for their co-operation.

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(3) Chilton, H.: "Performance of Natural-Draught Water-Cooling Towers," *Proceedings I.E.E.*, Paper No. 1232 S, January, 1952 (**99**, Part II, p. 440).

(4) Margen, P. H.: "The Application of Friction/Heat-Transfer Correlations to Cooling-Tower Design" (see page 290).

(5) Kennedy, Geoffrey F., and Margen, P. H.: Contribution to the discussion on the paper by B. Wood and P. Betts: "A Contribution to the Theory of Natural-Draught Cooling Towers," *Proceedings of the Institution of Mechanical Engineers*, 1950, **163**, p. 65.

(10) APPENDIX

The object of the Appendix is to describe fully the assumptions made and the methods of calculation used in constructing the charts described in the text.

In accordance with Section 2, an economic heat-rejection circuit requires that (*a*) = (*b*), where

(*a*) is the incremental annual investment in cooling tower, condenser or circulating-water system per degree Fahrenheit reduction in water temperatures at specified conditions and may be denoted by $\partial Z/Q\partial t$, $\partial Z_c/Q\partial t$ or $\partial Z_w/Q\partial t$ respectively.

(*b*) is the financial value of additional generator output obtained as a result of temperature reduction, which involves the incremental generator output, $\partial P/Q\partial t$, and various cost constants.

Sections 10.1 and 10.2 describe respectively the formulae from which (*a*) and (*b*) have been calculated, and Section 10.3 gives worked examples applying these formulae to the determination of one point on Figs. 4 and 5. Section 10.4 describes the calculations for miscellaneous points raised in the text.

The symbols used in these Sections are as follows:

a, a_1, a_2, a_3 and b = Power cost constants given in Table 6.
c_M, c_N = Cooling-tower cost constants defined by eqns. (1*a*) and (1*b*).
η_t = Turbo-generator efficiency factor defined in eqn. (10).
η_w = Pumping set efficiency.
h_1 = Enthalpy of atmosphere, B.Th.U./lb of dry air.
h''_m = Enthalpy of saturated air at algebraic mean circulating-water temperature, B.Th.U./lb of dry air.
K = Heat transfer coefficient for condenser, B.Th.U./sec-°F-ft².
L = Load factor of heat rejection to cooling tower.
L_F, L_w = Load factor of power supply to fans and pumps respectively.
P = Generator output, kW.
Q = Heat rejection to cooling tower, B.Th.U./sec.
q_e = Turbine-exhaust heat loading, B.Th.U./sec per square foot of net exhaust area.
S = Condenser-tube surface, ft².
t_{w1}, t_{d1} = Wet- and dry-bulb atmospheric temperatures, °F.
t = Steam temperature in condenser, °F.
y_M, y_N = "Atmospheric factors" in the cooling-tower performance equations (1*a*) and (1*b*).
Z = Annual cooling-tower costs, i.e. the sum of the tower capital charges, maintenance costs and fan power costs, £/annum.
Z_s = Annual condenser costs, i.e. the sum of the condenser capital charges, maintenance costs and costs of friction losses, £/annum.
Z_w = Annual costs affected by water quantity, £/annum.
θ_1, θ_2 = Outlet and inlet temperatures of the circulating water at the cooling towers, °F.
θ_m = Algebraic mean of the circulating-water temperatures.
$\Delta\theta$ = Water-temperature range = $(\theta_2 - \theta_1)$, °F.

Suffix *FL* is used to designate conditions when the tower is operated at full load.

(10.1) Performances and Costs of Heat-Rejection Plant

(10.1.1) Cooling-Tower Relations.

The basic cooling-tower performance relations used involve the assumption that a performance coefficient, *C*, of the type proposed by Chilton[3] is a constant for a given tower. Eqns. (5*a*) and (5*b*) in Reference 4 may then be rewritten as follows in terms of the total annual costs, *Z*, on the tower:

Mechanical draught: $$(h''_m - h_1) = y_M c_M (Q/Z)(a + a_1 + bL_F)^{1/3} \quad (1a)^*$$

Natural draught: $$(h''_m - h_1) = y_N c_N (Q/Z)^{2/3} \quad (1b)$$

The atmospheric factors, y_M and y_N in these expressions may be obtained from Figs. 1(*a*) and 1(*b*) in Reference 4, or more approximately from the formulae

$$y_M = 1{\cdot}29 + 0{\cdot}0025 t_{w1} + 0{\cdot}00018 t_{d1} \quad (2a)$$

$$y_N = 6{\cdot}1 - 0{\cdot}084 t_{w1} + 0{\cdot}158 t_{d1} \quad (2b)$$

The cost constants c_M and c_N have the following values for the three design examples considered in Reference 2:

Mechanical-draught tower with film-type packing: $c_M = 0{\cdot}76$
Natural-draught tower with film-type packing
Water allowed to fall into pond: $c_N = 0{\cdot}51$
Design incorporating collecting troughs: $c_N = 0{\cdot}50$

Splash-bar-type cooling towers have lower values of c_M and c_N, but the pumping-power consumptions are greater so that the overall economy is not greatly different. In the paper the

* The right-hand side of this equation can be replaced by $y_N (Q/D)^{2/3}$, where D is the duty coefficient defined by Chilton.[3]

Table 6

POWER COST CONSTANTS

Symbol	Constant	Assumed value
	Electricity Tariff:	
a	Initial component	£5·6 per kW-annum
b	Running component*	£16 for 8 760 kWh
	Incremental Power Component of Capital Charges on:	
a_1	Fan-motor set	£1·7 per kW-annum
a_2	Pump-motor set	£1·7 per kW-annum
a_3	Turbo generator	£2·2 per kW-annum
a_4	Average capital charges on tower, condenser, circulating-water system and turbine exhaust	£0·5 per annum for 3 414 B.Th.U./hour of heat rejection

Constants a, a_3 and a_4 are charged on the mean of the maximum demands in the three seasons.

* Corresponds to 0·44d./kWh.

values $c_M = 0{\cdot}65$ and $c_N = 0{\cdot}42$ are used, and these agree well with data* on splash-bar towers having a static pumping head of about 30 ft. Table 6 summarizes the assumed values of the fan-power constants, a, a_1, and b.

In the derivation of eqn. (1*a*) it is assumed that the most economic fan power for the particular load factor is selected in accordance with eqn. (13*a*) in Reference 3, i.e. that the capital charges and maintenance costs are twice as great as the costs of fan power, including the incremental power component of the fan capital charges.

By differentiating eqns. (1*a*) and (1*b*) one obtains the following expressions for the temperature reduction per unit additional annual investment in the cooling tower:

$$\text{Mechanical draught: } \frac{Q\partial t}{\partial Z} = y_M c_M\left[\frac{Q}{Z}\right]^2 (a+a_1+bL_f)^{1/3}\frac{d\theta_m}{dh''_m} \quad (3a)$$

$$\text{Natural draught: } \frac{Q\partial t}{\partial Z} = \frac{y_N c_N}{1{\cdot}5}\left[\frac{Q}{Z}\right]^{5/3}\frac{d\theta_m}{dh''_m} \quad . \quad . \quad . \quad . \quad . \quad (3b)$$

This can be evaluated with the assistance of Fig. 10, which shows $d\theta_m/dh''_m$ plotted against θ_m.

Eqns. (1*a*) and (1*b*) imply that the algebraic mean water temperature, θ_m, is independent of the temperature range of the water for a given heat rejection, Q. This is well supported by the test data analysed by Kennedy and Margen[5] and Chilton[3] in the normal operating range, but is known to be incorrect when the temperature range becomes large in relation to $(\theta_m - t_{w1})$. Curve (*a*) of Fig. 11 shows the estimated increase in θ_m per degree Fahrenheit increase in the water-temperature range in these circumstances. It represents the estimated mean conditions for splash-bar-type packings, and slightly lower values would apply for film-type packings. Curve (*b*) shows the corresponding integrated values of the increase in θ_m relative to the values implied by eqns. (1*a*) and (1*b*). These curves are used in the determination of the economic water-temperature range, as discussed later; they can also be used to derive a correction to eqns. (3*a*) and (3*b*), but this is insignificant in most practical cases.

(10.1.2) **Condenser Relations.**

For multi-pass condensers the logarithmic mean temperature difference between the circulating water and the steam equals the term Q/SK, in which S denotes the tube surface and K the heat-transfer coefficient. The rate of change of the condenser steam temperature with Q/SK and constant water-temperatures may be found from the term $dt/d(Q/SK)$ represented in Fig. 12.

The capital charges on a condenser can be taken to have a constant initial component and a variable component proportional to the tube surface, S. The water- and steam-side components of the heat-transfer resistance vary approximately with the exponents $-1/4$ of the appropriate friction power losses per unit tube surface. For an economic design, the "total annual condenser costs" (i.e. the capital charges, maintenance costs on the condenser, and the costs incurred by the water and steam side tube friction losses) can be represented by

$$Z_c = \text{Initial component} + cSK(a + bL)^{1/4} \quad . \quad . \quad (4)$$

It is assumed in this expression that the tube friction power is charged simply at the electricity tariff. Actually, the water-side friction power is slightly more expensive than this because it involves also capital charges on the pumps. However, the

* The following rates are assumed for capital charges and maintenance: reinforced-concrete works and excavations, 6·5%; external timber works fans, etc., 7·5%; internal timber works, 9·5%.

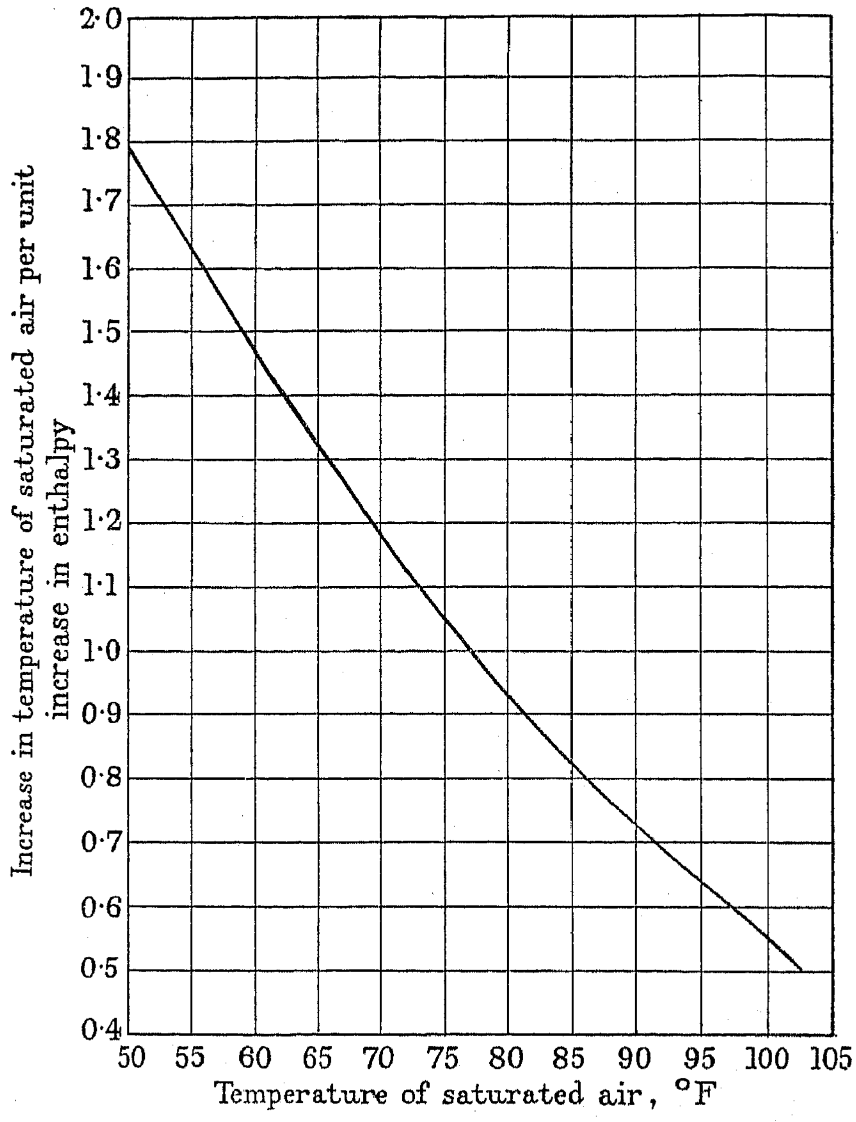

Fig. 10.—Gradient of temperature/enthalpy curve.

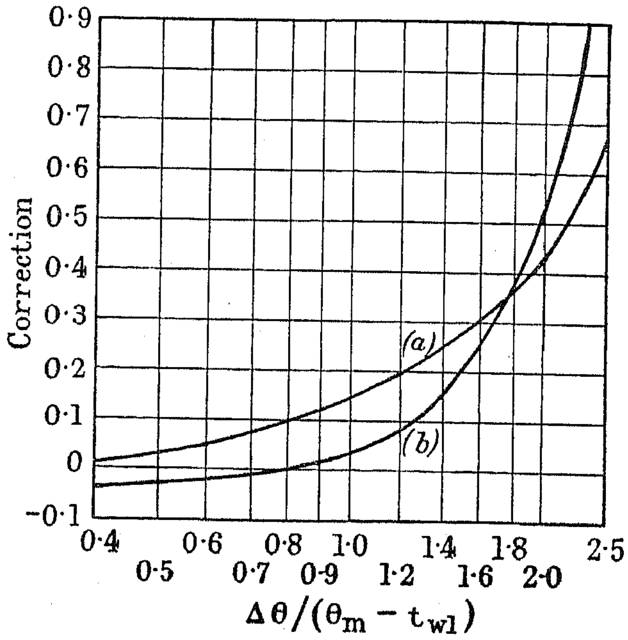

Fig. 11.—Corrections to mean water temperature for varying temperature range.

(a) $\dfrac{\delta(\theta_m - t_{w1})}{\delta\Delta\theta}$

(b) $\dfrac{(\theta_m - t_{w1})' - (\theta_m - t_{w1})}{\Delta\theta}$

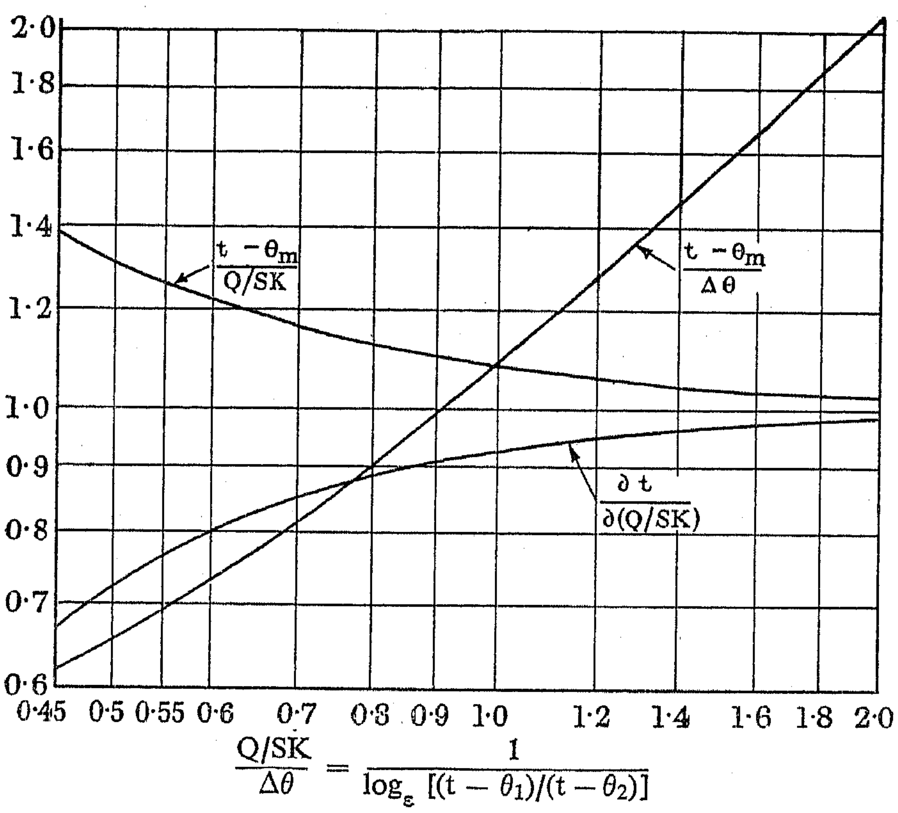

Fig. 12.—Temperature relations for condenser.

$t_s - \theta_m$ = Algebraic mean temperature difference.
Q/SK = Logarithmic mean temperature difference.
$\Delta\theta$ = Water-temperature range.

steam-side friction power is slightly less expensive, because an increase in that power reduces the required rating of the turbo-generator. These two factors approximately cancel out. The charts in the paper are based on $c = 0{\cdot}94 + 0{\cdot}005\Delta\theta$, i.e. they allow for a slight cost increase with increasing design temperature range, i.e. with increasing number of condenser water passes.

As pointed out in Section 3, the cost data available for condensers are not as precise as those for cooling towers, particularly as station building costs are affected.

From eqn. (4) the following expression is obtained for the temperature reduction per unit additional annual financial investment in the condenser:

$$\frac{Q\partial t}{\partial Z_s} = \frac{1}{c(a + bL)^{\frac{1}{4}}}\left[\frac{Q}{SK}\right]^2 \frac{\partial t}{\partial(Q/kS)} \quad . \quad . \quad . \quad (5)$$

This can be evaluated with the aid of Fig. 12. Also from the variation in c,

$$\frac{dZ_w}{Qd\Delta\theta} = \frac{0{\cdot}005(a + bL)^{1/4}}{Q/SK} \quad . \quad . \quad . \quad . \quad (6)$$

(10.1.3) **Circulating-Water Quantity.**

Since the water quantity equals $Q/\Delta\theta$, a reduction in the water quantity for constant Q produces an increase of the temperature range. It has already been pointed out that this is estimated to increase the mean circulating-water temperature produced by the cooling tower by the small amount indicated in Fig. 11.

Changing the water quantity for a condenser of given design affects the heat-transfer coefficient and temperature range. It is well known that the net result of these changes is to keep the terminal temperature difference at the hot end, $t - \theta_2$, practically constant over the practical range of conditions, the change being taken up by the temperature difference at the cold end, $t - \theta_1$. It follows that

$$\frac{\partial(t - \theta_m)}{\partial\Delta\theta} = \tfrac{1}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Since the friction head varies approximately with the 1·8th power of the water quantity, the variation of the pumping costs with changing temperature range, $\Delta\theta$, is

$$\frac{\partial Z}{Q\partial\Delta\theta} = \frac{(a + a_1 + bL_w)(H_0 + 2{\cdot}8H_F)}{738\eta_w\Delta\theta^2} \quad . \quad . \quad (8)$$

where H_0 is the static head, and H_F the effective mean friction head. H_F is slightly lower than the friction head obtained at full station load because the component of this head incurred by the common bus-pipes to the tower and by the tower nozzles is a function of the total water quantity. The charts in this paper are based on $H_0 = 30$ ft, $H_F = 23$ ft, $\eta_W = 0{\cdot}75$.

Combining the preceding equations, one obtains for the reduction in temperature per unit additional investment in the circulating water plant, power costs, and other items affected by $\Delta\theta$,

$$\frac{Q\partial t}{\partial Z_w} = \left[\frac{\dfrac{1}{2} + \dfrac{d(\theta_m - t_{w1})}{d\Delta\theta}}{\dfrac{(a + a_1 + bL)(H_0 + 2{\cdot}8H_F)}{738\eta_w\Delta\theta^2} - \dfrac{0{\cdot}005(a+bL)^{1/4}}{Q/KS}}\right] \quad . \quad (9)$$

Fig. 4(*b*) is based on this question, the term $\partial(\theta_m - t_{w1})/\partial\Delta\theta$ being obtained from Fig. 11. Towers employing film-type packings have lower values of this term and lower values of the static head, H_F. These effects are estimated to cancel approximately, so that the economic temperature ranges calculated in the paper are estimated to apply to film-type packings also.

(10.2) Incremental Generator Output

The curves of incremental generator output in Fig. 3 are based on the expression

$$\frac{\partial P}{Q\partial t} = \frac{3\,600}{3\,414}\eta_t\left[\frac{1}{460 + t} - \frac{q_e^2}{1\,556g}\frac{V_s}{L_s^2}\left(\frac{2dV_s}{L_s dt} - \frac{3V_s dL_s}{L_s^2 dt}\right)\right] \quad (10)$$

where the second term inside the square brackets represents the rate of change of the turbine leaving loss, $q_e^2V_s^2/1556gL_s^3$, with respect to t and

η_t = Factor allowing for blade efficiency on the last turbine wheel, feed heating and cycle imperfections, etc. (taken to be 0·7 in constructing Fig. 3).
V_s = Specific volume of steam, ft³/lb.
L_s = Latent heat of steam, B.Th.U./lb.
g = Gravitational acceleration, ft/sec².

These expressions neglect the effect of condensed moisture, i.e. assume that there is perfect drainage.

The financial value of the incremental generator output can be found from a two-part formula, the first part being the energy component of the electricity tariff and the second a charge of $(a - a_3 + a_4)$ per kilowatt increase in the maximum output, where a is the fixed component of the electricity tariff, a_3 allows for the additional capital charges on the turbo-generator required to make the additional capacity available, and a_4 allows for the reduction in the heat rejection resulting from the increase in electricity output at constant station-heat intake. This reduction in the heat rejection makes it possible to employ a slightly smaller tower, condenser and turbine exhaust for the same performance.

(10.3) Sample Calculations

(10.3.1) Economic Duty Conditions.

From Figs. 4(a) and 5 the economic temperature conditions for natural-draught towers designed for $L = 0{\cdot}45$ and $q_e = 1\,500$ B.Th.U./sec-ft^2 are as follows:

$$(\theta_m - t_{w1}) = 25{\cdot}2°\text{F}; (t - \theta_m) = 16{\cdot}8°\text{F}; \Delta\theta = 18{\cdot}6°\text{F}$$

These conditions correspond to the following design data:

Cooling tower: $Z/Q_{FL} = 0{\cdot}1148$, (£/annum)/(B.Th.U./sec).
Condenser: $Q_{FL}/SK = 14{\cdot}9°$F.

Table 7 illustrates the method of checking that these conditions are economic.

(10.3.2) Comparison of Natural- and Mechanical-Draught Towers.

From Figs. 4(a) and 4(b) the economic temperature conditions for towers designed for $L = 0{\cdot}45$ and $q_e = 1\,500$ B.Th.U./sec-ft^2 are as follows:

Natural draught: $(\theta_m - t_{w1}) = 25{\cdot}2°$F.
Mechanical draught: $(\theta_m - t_{w1}) = 22{\cdot}8°$F.

From item (b) in Table 7 the annual load factor of the fans is $0{\cdot}575$, so that $(a + a_1 + bL_F)$ amounts to £16·5 per kW-annum. Then from eqns. ($1a$) and ($1b$) the corresponding annual cooling-tower costs (including the cost of fan power but excluding the cost of pumping) are:

Natural draught, Z/Q_{FL} ..	0·1148 £/annum per B.Th.U./sec
Mechanical draught, Z/Q_{FL} ..	0·1485 £/annum per B.Th.U./sec
Difference	0·0337 £/annum per B.Th.U./sec
Difference in costs of operation [from Table 8, item (h)]	0·02459 £/annum per B.Th.U./sec
Net difference in costs (in favour of natural draught)	0·00911 £/annum per B.Th.U./sec

(10.4) Miscellaneous Points

(10.4.1) Condenser and Circulating-Water Design for River Station.

In the derivation of the figures for Table 3 the river temperatures were assumed to be 42, 51 and 60°F in the winter, intermediate and summer seasons respectively. The pumping head was assumed to be 20ft.

(10.4.2) Cost Comparison between Correct and Incorrect Design.

Table 4 is based on the following assumptions:

(a) The same condenser to be used for both designs.

(b) The condenser friction heads are in proportion to the 1·8th power of the water quantities, i.e. are 7 and 11ft respectively.

(c) The friction heads in the piping, culverts and valves are the same in both schemes, larger sections being used in the scheme with the larger water quantity.

(d) The calculations take account of the performance corrections for different water-temperature ranges shown in Fig. 11, curve (b).

(10.4.3) Temperature-Range Regulation.

In modern generating stations, one full-duty or two half-duty circulating-water pumps are usually provided per turbine. When some of the turbines are off load, the reduction in the friction head produces a slight reduction in the water-temperature range, but this has been ignored in the calculations.

Table 7

CHECK ON ECONOMIC DUTY CONDITIONS

Item	Winter		Intermediate season		Summer	
	1	2	3	4	5	6
Cost Multipliers						
(a) Heat load as fraction of full station load	1	⅔	1	⅓	⅔	⅓
(b) Duration as fraction of year	0·09	0·12	0·11	0·12	0·13	0·13
(c) Product of load and duration	0·09	0·08	0·11	0·04	0·0867	0·0433
(d) Period of maximum demand in season	1	—	1	—	1	—
(e) Cost multiplier $A = 16 \times (b) + 1{\cdot}3 \times (d)$	2·74	1·92	3·06	1·92	3·38	2·08
(f) Cost multiplier $B = (a) \times (e)$	2·74	1·28	3·06	0·64	2·26	0·69
Incremental generator output						
(g) Atmospheric wet-bulb temperature, °F	41·00	41·00	49·00	49·00	57·00	57·00
(h) Mean water temperature, °F	68·30	63·05	74·20	62·82	75·60	69·57
(j) Steam temperature, °F	85·10	79·85	91·00	79·62	92·40	86·34
(k) $dM/Qdt \times 10^3$ (from Fig. 3)	0·877	0·680	1·010	0·662	1·035	0·906
Temperature reductions for unit additional investment						
(l) Tower: Qdt/dZ [from eqn. ($3b$)]	121	69·3	113·2	23·4	59·2	21·5
(m) Condenser: $Q_{FL}dt/dZ_s$ [from eqn. (5)]*	102·5	102·5	102·5	102·5	102·5	102·5
(n) Circulating water: $Q_{FL}dt/dZ_w$ [from eqn. (9)]* ..	90	101	96	121	109	126
Products						
(o) Tower: $(f) \times (k) \times (l) \times 10^{-3}$	0·291	0·090	0·341	0·030	0·207	0·041
(p) Condenser: $(e) \times (k) \times (m) \times 10^{-3}$	0·246	0·089	0·317	0·044	0·240	0·064
(q) Circulating water: $(e) \times (k) \times (n) \times 10^{-3}$	0·217	0·088	0·298	0·051	0·255	0·079

The totals for items (o), (p) and (q) are 1·000, 0·988 and 1·000 respectively, i.e. practically unity. Hence the incremental investment just balances the incremental return so that the stated duty conditions are economic.

* With the present practice of block-load allocation the condensers would normally operate practically on full load. Hence Q_{FL} is substituted for Q in eqns. (5) and (9).

Table 8

DIFFERENCE IN COSTS OF OPERATION

Item	Winter		Intermediate season		Summer	
	1	2	3	4	5	6
(a) Heat load as fraction of full station load	1	$\frac{2}{3}$	1	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{1}{3}$
(b) Fraction of mechanical-draught towers on load	1	1	1	$\frac{2}{3}$	1	$\frac{2}{3}$
(c) Mean water temperature, °F						
(i) Natural draught	68·30	63·05	74·20	62·86	75·60	69·57
(ii) Mechanical draught	67·00	59·73	71·80	61·75	71·13	68·02
(iii) Difference	1·30	3·32	2·40	1·11	4·47	1·55
(iv) Mean	67·65	61·40	73·00	62·31	73·36	68·80
(d) Mean steam temperature, °F	84·45	78·20	91·80	79·11	90·13	86·60
(e) Incremental generator output $\times 10^3 \partial P/Q\partial t$ [from item (d) and Fig. 3]	0·859	0·602	1·021	0·647	0·992	0·912
(f) Cost multiplier [from Table 7, item (f)]	2·74	1·28	3·06	0·64	2·26	0·693
(g) Product: (ciii) × (e) × (f)	3·05	2·56	7·50	0·47	10·03	0·98
(h) Total for item (g), 10^{-3}(£/annum)/B.Th.U./sec)	24·59					

Table 9

LEADING PARTICULARS OF COMBINED RIVER AND TOWER SCHEME

(Hypothetical Scheme)

Item	Winter		Intermediate season		Summer	
	1	2	3	4	5	6
(a) Station heat rejection, B.Th.U./sec	400 000	266 000	400 000	133 000	266 000	133 000
(b) Mean river discharge, lb/sec	80 000	45 000	40 000	25 000	16 500	34 000
(c) Mean permissible temperature rise, °F	8	8	6	6	4	4
(d) Permissible heat rejection to river, B.Th.U./sec	640 000	360 000	240 000	150 000	66 000	136 000
(e) Residual heat rejection to towers, B.Th.U./sec	—	—	160 000	—	200 000	—
(f) Mean river temperature, °F	42	42	51	51	60	60
(g) Mean atmospheric wet-bulb temperature, °F	41	41	49	49	57	57
(h) Tower heat loading, (Q/Z), (B.Th.U./sec)/(£/annum)	—	—	8·45	—	10·56	—
(j) Mean tower-water temperature, °F			72·2		81	
(k) Tower outlet-water temperature, °F	—	—	66·2	—	72	—
(l) Condenser inlet-water temperature, °F	42	42	51	51	66	60
(m) Condenser outlet-water temperature, °F	63	63	78·2	69	90	78
(n) Condenser steam temperature, °F	70	70	85·2	76	97	85
(o) Condenser discharge, lb/sec	19 000	12 700	14 700	7 400	11 100	7 400
(p) Tower discharge, lb/sec	—	—	14 700	—	11 100	—
(q) Condenser-circuit pumping head, ft	20	20	11·5	25·3	17·5	25·3
(r) Tower-circuit pumping head, ft	—	—	32·9	—	34·0	—
(s) Total pumping power, kW	668	446	1 145	299	1 005	299

Intentional increase in the water-temperature range should take place when

$$\frac{\partial P}{Q\partial t} < \frac{R(H_0 + 2\cdot 8H_F)(0\cdot 5 + \partial\theta_m/\partial\Delta\theta)}{738\eta_w\Delta\theta^2} \quad . \quad . \quad (11)$$

where the factor R is unity when constant-efficiency variable-speed pumps are used, and less than unity in all other cases. A value of $R = 0\cdot 56$ was used in the calculations to take account of the more restricted facilities for water regulation when only a limited number of constant-speed pumps are available.

When the above inequality is satisfied, the right-hand side should be used instead of $\partial P/Q\partial t$ in establishing the financial value of a 1°F reduction in temperature.

(10.4.4) **Reduction in Number of Cells on Load.**

For an economic mechanical-draught tower design the annual costs of the fan power (including the incremental component of the fan charges) amount to $Z/3$, i.e. are equal to half the capital charges and maintenance costs. From this it can be shown that it is economic to cut out cells when

$$\frac{\partial P}{Q\partial t} < \frac{Zdh''_m/d\theta_m}{3Q(h''_m - h_1)(a + a_1 + bL)} \quad . \quad . \quad (12)$$

on the assumption that eqn. (1a) is satisfied. This relation was used to plot curve (a) in Fig. 8.

(10.4.5) **Effect of Climatic Conditions.**

The economic temperature difference $(t - \theta_m)$ across the condenser was not calculated in the construction of Fig. 7, but was assumed to be two-thirds of the economic temperature difference, $(\theta_m - t_w)$, across the towers. This is in accordance with the average ratio found from Figs. 4 and 5.

(10.4.6) **Combined River and Tower Scheme.**

Table 9 gives leading particulars of the scheme on which the cost comparison in Table 5 is based. In practice, more than six periods would generally be used to represent the various combinations of river discharges and station load encountered, but it is considered that the six periods shown are sufficient to illustrate the general method of approach and to give a realistic assessment of the savings which can be achieved.

The effect of vacuum on the operating costs is obtained by comparing the steam temperatures in item (n) of Table 9 with the steam temperatures in item (j) of Table 7, and then applying a procedure similar to that employed in Table 8.

[The discussion on the above paper will be found on page 300.]

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Paper No. 1705 S
Aug. 1954

THE APPLICATION OF FRICTION/HEAT-TRANSFER CORRELATIONS TO COOLING-TOWER DESIGN

By P. H. MARGEN, B.Sc.(Eng.), Associate Member.

(*The paper was first received* 30*th September*, 1953, *and in revised form* 28*th May*, 1954. *It was published in August*, 1954, *and was read before the* SUPPLY SECTION 5*th January*, 1955.)

SUMMARY

The thesis of this paper is that friction and heat-transfer properties of cooling-tower packings are correlated, i.e. that an improvement in the heat-transfer properties can be obtained at the expense of an increase in friction. For any given shell design and packing surface a definite friction factor will then produce the best cooling-tower performance.

The precise nature of the friction/heat-transfer relation depends on the method of changing the shape of the packing, e.g. a progressive change in the alignment of corrugated sheets to produce progressively narrower constrictions in the air-flow path. The limited experimental evidence now available, however, suggests that differences between various methods are not pronounced, i.e. that the results for all film-type packings free from the more obvious design faults are reasonably well represented by a general friction/heat-transfer correlation. For this correlation a chart is prepared from which the optimum friction factor, the economic packing surface per unit ground area and the corresponding cooling-tower performance coefficient can be read off for any values of two design constants, namely the air-flow resistance of the tower shell, and the comparative cost of extending the tower ground area and the packing surface. The values of these design constants are discussed for various applications, and it is shown that the optimum friction factor can vary over a range of 0·1–0·6, being lowest for small mechanical-draught towers situated on expensive ground, and highest for large natural-draught towers. Methods of determining the economic fan power or chimney height are described and illustrated by worked examples. With the aid of the design chart, economic mechanical- and natural-draught tower designs can be prepared very quickly.

For those film-type packings which do not quite satisfy the general correlation, the design chart may be used in conjunction with two correction factors. For larger departures from the general correlation, such as those to be expected from splash-bar packings, individual design charts can be constructed by the methods described.

LIST OF PRINCIPAL SYMBOLS

A = Mean horizontal area of tower at packing level, ft^2.
a = Area of packing surface per cubic foot of space, ft^{-1}.
b, c = Constants in the friction/heat-transfer correlation, eqn. (8).
C = Cooling-tower performance coefficient.
D = Internal diameter of natural-draught chimney at mean packing level, ft.
d = Scale dimension of packing [= $4A$/(flow-path perimeter)], ft.
η_w, η_F = Efficiency of pumping and fan sets respectively.
F = Resistance of tower shell to air flow (= head loss in velocity heads at reference area A).
f = Friction number of packing (= head loss in velocity heads at reference area A per unit s).
G = Dry air-mass flow rate per unit A, lb/sec-ft.
g = Gravitational acceleration, ft/sec^2.
H = Height of natural-draught chimney above mean packing level, ft.
h = Mean enthalpy of air in the main current, B.Th.U per pound of dry air.
h'' = Enthalpy of saturated air at the mean water temperature, B.Th.U. per pound of dry air.
k = Heat-transfer number of packing (= mass transfer coefficient/G).
M = Factor defined by eqn. (12).
m, m_f = Exponents defining the effect of the water rate on the transfer numbers [eqns. (17*a*) and (17*b*)].
n, n_f = Exponents defining the effect of the air rate on the transfer numbers [equations (17*a*) and (17*b*)].
p = Air power expended per unit A, ft-lb/sec-ft^2.
q = Heat loading of tower per unit A, B.Th.U./sec-ft^2.
r = Ratio: (Total air weight)/(Dry air weight).
s = Packing surface per unit A.
t_w, t_d = Wet-and-dry-bulb air temperatures, °F.
w = Water-flow rate per unit A, lb/sec-ft^2.
y_M, y_N = Atmospheric factors defined by eqn. (3).
z_s, z_A, z_F, z_w, z_H = Cost factors relating to packing surface, horizontal tower area, fan power, pumping power and chimney height respectively (units given in text).
ρ = Nominal density of air, pounds of dry air per cubic foot of air-vapour mixture.
μ = Viscosity of air, lb/sec-ft^2.
θ = Water temperature, °F.

Subscripts 1, 2 and m are used to designate respectively values at the air inlet, air exit, and point of 50% heat release in the packing (i.e. at the algebraic mean water temperature). Prefix Δ denotes the mean change of value between conditions 1 and 2.

(1) INTRODUCTION

When a fluid flows through a channel containing a solid system, various resistances to fluid flow (or friction factors) can be obtained by adjusting the shape of the solid system. It has been realized for a long time that the conditions which result in high friction factors produce violent eddies in the fluid and thereby increase the rate at which heat can be transmitted from the fluid to the solid system. In other words, the friction and heat-transfer properties of the system are correlated, so that it is impossible to achieve high heat-transfer properties with a low friction factor. Yet there is a compromise between these conflicting design aims which will give the best performance, and it is the main purpose of the paper to show how this compromise can be found for cooling-tower packings.

The first requirement for this task is the definition of convenient "indexes" of the friction and heat transfer properties. The non-dimensional indexes selected for this paper are

(*a*) A friction number, f, defined by an equation of the Fanning type, i.e.

$$\frac{\text{Packing air-friction power}}{\text{Packing surface}} = \frac{frG^3}{2g\rho^2} \quad . \quad . \quad . \quad . \quad (1)$$

(*b*) A heat-transfer number, k, defined by the following equation for the rate of heat transfer, δq, from the packing surface element, δs:

$$\delta q/\delta s = kG(h'' - h) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

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Eqn. (2) is similar to the basic heat-transfer equation adopted by Merkel[1] in 1926 and by subsequent cooling-tower investigators, who have usually termed the dimensional product kG the "matter transfer coefficient" and have given it the symbol K.

(2) THE PERFORMANCE COEFFICIENT

Introducing the packing surface, s, per unit horizontal area of the tower, and the shell resistance, F (which arises mainly from losses at the air entry and exit), the equations for air flow may now be written:

(*a*) With fans developing an air power p per unit horizontal area

$$y_M G = [p/(F + fs)]^{1/3} \quad \quad (3a)$$

(*b*) With a natural-draught chimney of effective height H

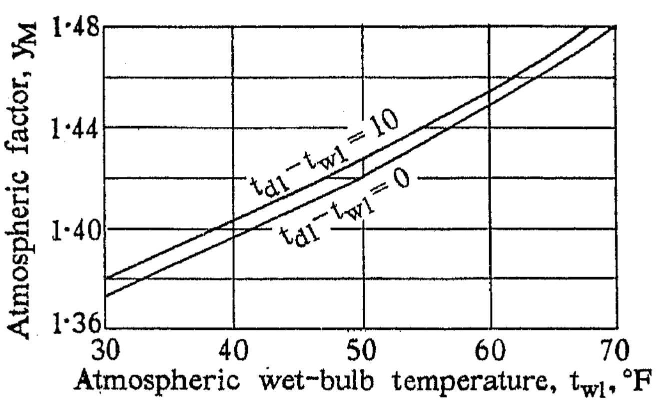
$$y_N G = [qH/(F + fs)]^{1/3} \quad \quad (3b)$$

where

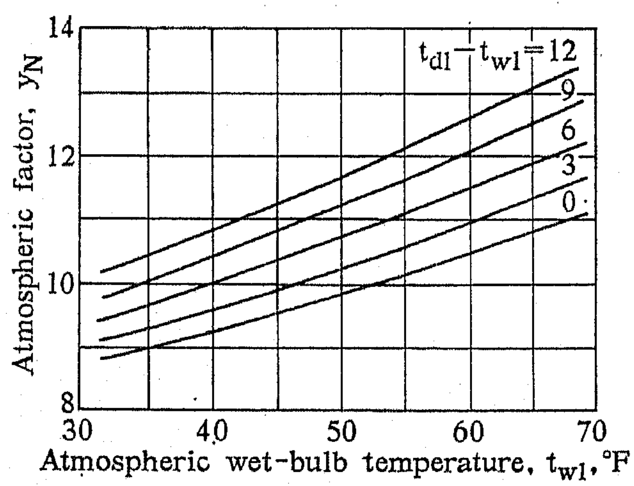
$$y_M = \left(\frac{r_m}{2gp_m^2}\right)^{1/3}$$

$$y_N = y_M\left[\frac{\rho_m r_m \Delta h}{\Delta(\rho r)}\right]^{1/3}$$

The factors y_M and y_N defined above depend mainly on the atmospheric conditions and may be obtained from Figs. 1(*a*) and 1(*b*) respectively to a good degree of approximation. The construction of these diagrams is described in Section 14.1.2.



(*a*)



(*b*)

Fig. 1.—Atmospheric factors.
(*a*) Mechanical draught.
(*b*) Natural draught.

From eqn. (2) the heat-transfer equation for the tower can be obtained by performing an approximate integration, i.e.

$$(h''_m - h_m) = q/skG \quad \quad (4)$$

whence, by adding the identity $(h_m - h_1) \equiv q/2G$ to eqn. (4) and eliminating the air rate, G, from eqn. (3*a*) or (3*b*), one obtains the basic performance equations used in this paper, namely

$$\text{With mechanical draught: } (h''_m - h_1) = Cy_M qp^{-1/3} \quad \quad (5a)$$

$$\text{With natural draught: } (h''_m - h_1) = Cy_N q^{2/3}H^{-1/3} \quad \quad (5b)$$

where

$$C = (F + fs)^{1/3}(1/sk + 1/2) \quad \quad (6)$$

The enthalpy difference, $(h''_m - h_1)$, in these expressions can be obtained from the atmospheric wet-bulb temperature, t_{w1}, and the algebraic mean of the circulating water temperatures, θ_m, using standard hygrometric tables or the chart, Fig. 2.

The performance coefficient, C, proposed by Chilton[3] in 1952 completely defines the capabilities of the packing and shell of a natural- or mechanical-draught tower per unit horizontal area.* It is, in fact, an inverse figure of merit, since a high value of C corresponds to a low capability, i.e. to high water temperatures for a given heat loading and air power or chimney height. Eqn. (6) shows very clearly the effect of the packing friction number, f, and the packing heat-transfer number, k, on the tower performance, and therefore forms a convenient basis for the discussion in the paper.

The use of eqns. (5) and (6) in conjunction with Figs. 1 and 2 involves two approximations discussed in Section 14, namely the approximate integration of the heat-transfer equation represented by eqn. (2),† which usually involves errors within +2% to −3%, and the approximate values of the atmospheric-draught factors given by Fig. 1, which usually involve errors of less than 1% in y_M, and less than 3% in y_N.

(3) COOLING-TOWER PACKINGS

Fig. 3 shows various forms of cooling tower packings, and Table 1 gives the corresponding friction and heat-transfer numbers. Arrangements (*a*)–(*k*) are referred to as film-type packings, because most of the water surface is in the form of a film covering a solid system. The remaining two arrangements are splash-bar packings, in which water drops make an appreciable contribution to the transfer surface.

Arrangement (*a*) is a hypothetical packing composed of smooth continuous sheets of negligible thickness covered by a falling water-film which has a velocity negligible compared with that of the rising air current. For this hypothetical packing the extended Reynolds analogy‡ predicts that

$$k = f/2 = 0{\cdot}025(Gd/\mu)^{-0{\cdot}2} \quad \quad (7)$$

e.g. $k = 0{\cdot}004$, $f = 0{\cdot}008$ for the typical air-flow Reynolds number, $(Gd/\mu) = 10\,000$.

Arrangement (*b*) is a falling-film tower, which is similar to (*a*) except that the boards have an appreciable thickness and the water-film velocity is not negligible. As a result, the relative velocity between the air current and the water-film surface is X times the nominal or empty tower velocity, G/ρ, whence the heat-transfer and friction numbers become respectively $X^{0{\cdot}8}$ and $X^{1{\cdot}8}$ times the value given by eqn. (7), e.g. $0{\cdot}0061$ and $0{\cdot}021$ when $X = 1{\cdot}7$ and $(Gd/\mu) = 10\,000$. Arrangements (*c*)–(*f*), composed of wooden boards, give progressively higher friction by introducing gaps between the boards or by crossing the boards to produce "grid" arrangements. Test results for

* The definition employed by Chilton differs in minor respects, i.e. in the use of the ground area of the tower instead of the area at the mean packing level, and the use of Merkel's approximate integration of the heat transfer equation instead of the approximate integration used in eqn. (2). This was first proposed by Kennedy and Margen[4] in 1950. For a given tower, C can vary to a very slight extent with operating conditions as discussed in Section 10.

† In the past an alternative approximation proposed by Merkel[1] has generally been used, but this does not give any greater accuracy and is less convenient to apply. Lichtenstein[5] demonstrated in 1943 that all approximations of that type can result in appreciable errors in certain extreme cases. These are, however, rarely met in practice and can be guarded against by inspection of the chart described in Section 14.1.1.

‡ See Section 14.1.3 for discussion of accuracy of this analogy.

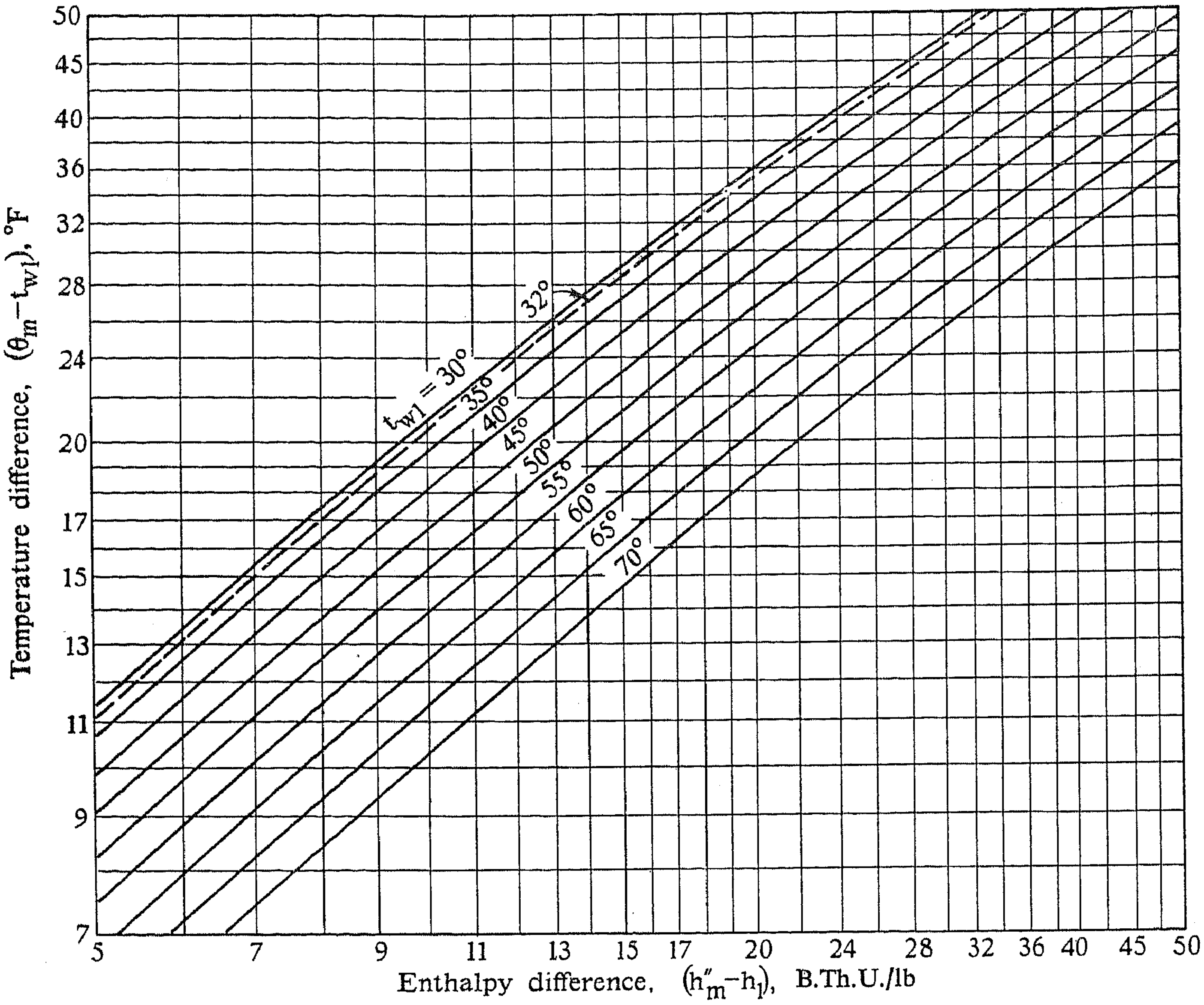


Fig. 2.—Relation between temperatures and enthalpy difference.
Plotted from Reference 2.

Table 1

PACKING PERFORMANCE DATA

Packing	Description of packing	Friction number f	Heat-transfer number k	Surface/volume ratio a	Test-flow rates w	Test-flow rates G	Reference
				ft^{-1}	lb/sec.ft^2		
	Parallel plates						
(*a*)	Thin continuous plates*	0·008	0·004	—	—	—	—
(*b*)	Thick continuous plates†	0·021	0·0061	—	—	—	—
(*c*)	Parallel spaced boards	0·072	0·0072	13·7	0·35	0·5	10
	Grid arrangements						
(*d*)	Deep serrated grids	0·144	0·0128	13·7	0·35	0·5	10
(*e*)	Shallow serrated grids	0·23	0·0197	13	0·68	0·59	9
(*f*)	Shallow plain grids	0·30	0·0135	30	0·61	0·41	9
	Corrugated sheets						
(*g*)	Vertical arrangement‡	Low friction		—	—	—	3
(*h*)	Horizontal arrangement‡	Medium friction		—	—	—	—
(*i*)	Horizontal staggered arrangement‡	High friction		—	—	—	—
	Rings						
(*j*)	Stacked rings	0·72	0·0132	25	1·20	0·37	9
(*k*)	Random rings	10·3	0·025	58	0·835	0·181	11
	Splash bars						
(*l*)	Wide pitch	Low friction		1–3	—	—	—
(*m*)	Narrow pitch	High friction		1–3	—	—	—

* Calculated for Reynolds analogy, assuming $(Gd/\mu) = 10\,000$, $X = 1{\cdot}0$.
† Calculated for Reynolds analogy, assuming $(Gd/\mu) = 10\,000$, $X = 1{\cdot}7$.
‡ Packings (*g*) and (*h*), and modified form of packing, (*i*), have been tested in experimental tower, but results have not yet been published; packing (*g*) was fitted in commercial tower tested by Chilton,[3] but transfer numbers were not reported.
Note.—Data fairly similar to those for packings (*e*), (*f*), (*j*) and (*k*) are also given in Reference 12.

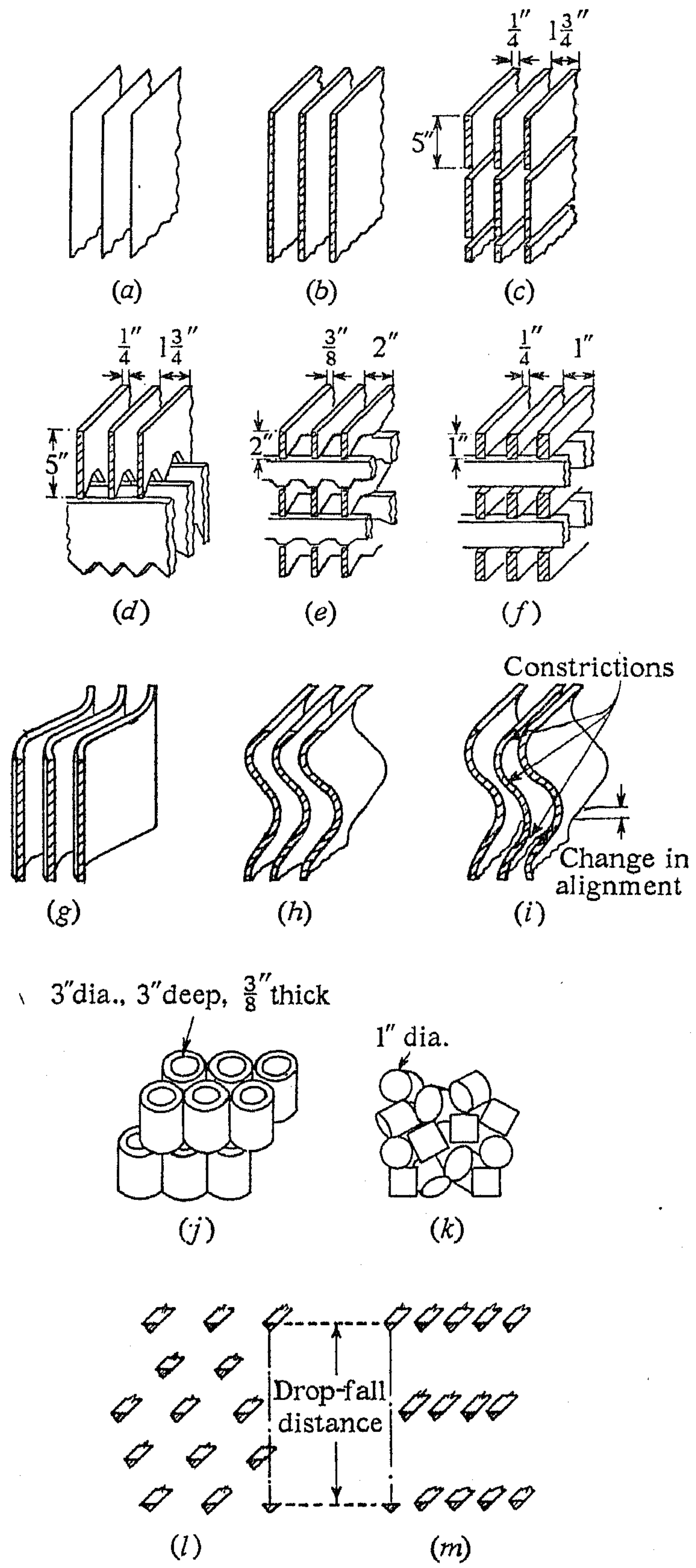


Fig. 3.—Cooling-tower packings.

Not to scale; see Table 1 for description and performance of packings.

these arrangements are available and are shown in Table 1. By employing boards having a low depth and a low pitch/thickness ratio, very high friction factors can be attained.

Packings (*g*), (*h*) and (*i*) are composed of corrugated sheets. When the corrugations run vertically, as in arrangement (*g*), a falling-film tower is, in effect, obtained. The friction can be increased by assembling the sheets with the corrugations running horizontally [arrangement (*h*)] so that the air-flow path contains numerous direction changes. Still higher values of the friction number result if the alignment of the sheets is altered to produce successive constrictions in the air-flow path, as shown by arrangement (*i*).

With splash-bar packings, such as arrangements (*l*) and (*m*), the friction numbers of the solid system can be varied by altering the horizontal and vertical pitching of the boards without changing the distance of fall of the drops. The method of determining the optimum friction factors is then the same as for film-type fills, but the friction/heat-transfer correlations are more complicated because of the introduction of drop surface. For that reason splash-bar packings are not dealt with in detail in the present paper.

It will be understood from the above examples that the friction numbers of cooling-tower packings can be varied over a wide range without changing the amount of packing material required, and consequently without appreciably changing the costs.

(4) FRICTION/HEAT-TRANSFER CORRELATIONS

The first attempt to correlate friction and heat-transfer properties appears to have been made by Colburn and King,[6] who plotted the heat-transfer factor against the pressure drop along tubes containing various baffles and packings. They found that the results for a given air rate and tube diameter could be represented reasonably well by single line. More recently Kays and London[7] described correlations for finned tubes between a relative heat-transfer factor and a relative friction-power constant. For the purpose of the present paper, plotting the heat-transfer number k against the friction number f to logarithmic scales, as shown in Fig. 4, is preferable to the correlations given in the literature.

In Fig. 4, points A and B represent the previously mentioned transfer numbers for the Reynolds analogy and the falling-film tower respectively, while the remaining points represent test results for the film-type packings of corresponding designations shown in Fig. 3.

In addition, a number of points marked by crosses are included and these represent the friction and heat-transfer numbers for dry-surface heat exchangers composed of bundles of tubes arranged perpendicular to an air stream. The points are calculated for an air-flow Reynolds number of 10 000 from empirical equations cited by McAdams,[8] as detailed in Fig. 4.

It will be noticed that most points lie reasonably close to the continuous line which is closely approximated by the broken line over the range of interest, i.e. $k = 0{\cdot}008$–$0{\cdot}032$. The worst exceptions are packings (*j*) and (*k*), composed respectively of stacked and random arrangements of rings. Clearly the random arrangement cannot produce uniform air and water distributions, and the stacked arrangement results in inadequate air flow between the rings, because of the low hydraulic radii of these passages. These features could account for the bad performances of these two packings.

The experimental evidence suggests that transfer numbers of packings which are free from the more obvious undesirable features are approximately represented by the broken line over the range of interest, i.e. by the equation

$$250f = (250k)^3 \quad . \quad . \quad . \quad . \quad . \quad (8a)$$

For packings slightly worse or better than the above correlation one may introduce the correction factor, b, writing

$$250f = b(250k)^3 \quad . \quad . \quad . \quad . \quad . \quad (8b)$$

while for greater precision the equation

$$250f = b_1(250k)^c \quad . \quad . \quad . \quad . \quad . \quad (8c)$$

may be used and experiments may be conducted to determine the values of b_1 and c for the particular method of varying the friction number, e.g. for a progressive change of the alignment of corrugated sheets from arrangement (*h*) to arrangement (*i*).

In the subsequent discussion it is first assumed that eqn. (8*a*) applies. Later the treatment required for eqns. (8*b*) and (8*c*) is described.

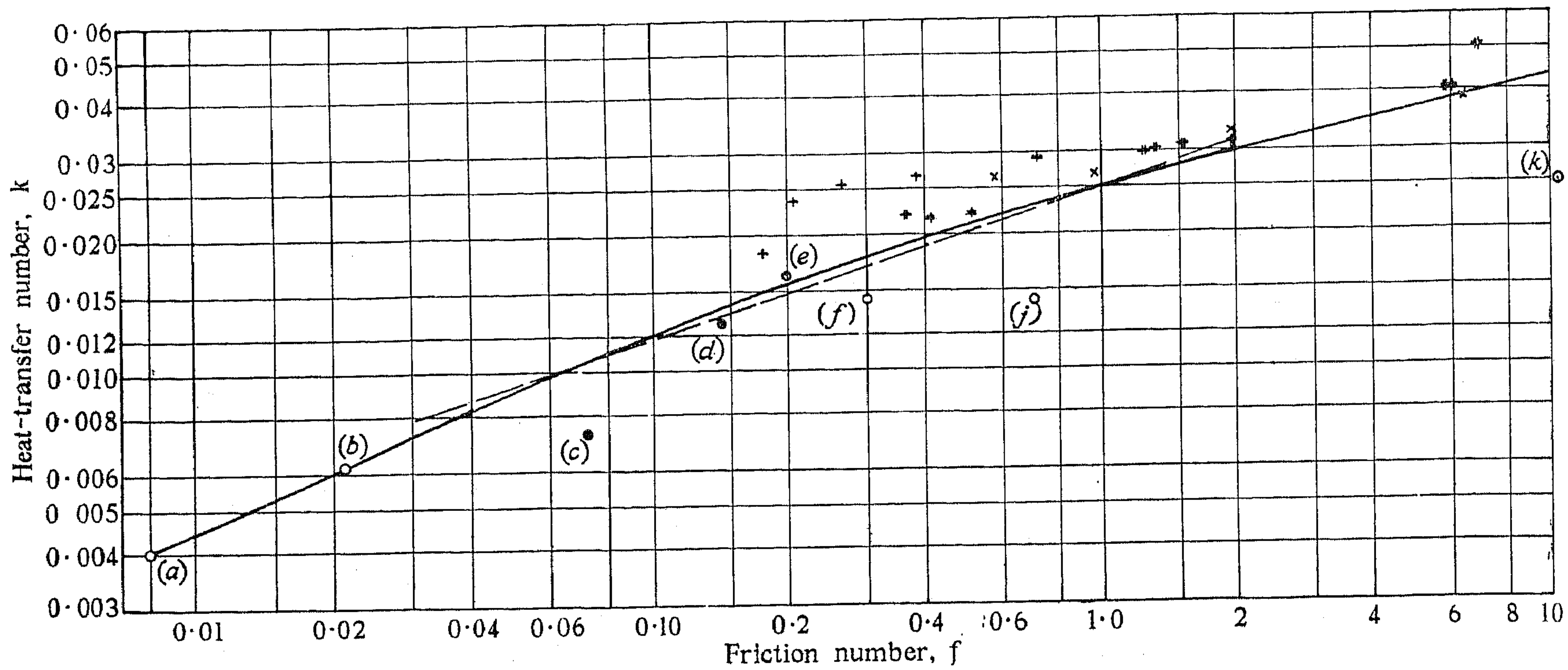


Fig. 4.—Friction/heat-transfer correlation.

——— Law suggested by data.
— — — Linear approximation over range of interest.

Points (*a*)–(*j*) refer to film-type packings illustrated in Fig. 3 and described in Table 1.
Crosses refer to data on air flow perpendicular to 10 rows of tubes calculated for Gd/μ from the following formulae and Tables in McAdams:
Friction: p. 126, eqns. (19) and (19*a*).
Heat transfer, staggered arrangements: p. 226, eqn. (7) with constants by Tucker (p. 227).
Heat transfer in line arrangement: Table V, p. 228.

Conversions used:

Symbols for this paper:	G	d	kG
Symbols used by McAdams:	$G_{max}(r_t - 1)/r_t$	$2r_tD_0$	h/c_p

Key:
In line arrangement for $r_L = 1\cdot25,\ 1\cdot5,\ 2\cdot0$ and $3\cdot0$:
+ $r_t = 1\cdot25$
‡ $r_t = 1\cdot5$
╫ $r_t = 2\cdot0$
$r_t = 3\cdot0$

× Staggered arrangements for all values of r_L and following values of r_t: $1\cdot25,\ 1\cdot5,\ 2\cdot0,\ 3\cdot0$.

(5) OPTIMUM HEAT-TRANSFER NUMBER

By combining eqns. (6) and (8*a*) one obtains for the cooling-tower performance coefficient,

$$C = (F + 250^2k^3s)^{1/3}(1/ks + 1/2) \quad . \quad . \quad . \quad (9)$$

which attains the minimum value

$$C = 0\cdot5F^{1/3}[1 + (500/s)^{1/2}(2/F)^{1/4}]^{4/3} \quad . \quad (10)$$

when $\qquad F/fs = ks/2$

i.e. when $\qquad k = (2F)^{1/4}/(250s)^{1/2} \quad . \quad . \quad . \quad . \quad (11)$

Any value of k greater or smaller than that given by eqn. (11) would produce a higher performance coefficient than that given by eqn. (10), i.e. a worse performance. Hence eqn. (11) defines the optimum value of the heat-transfer number and also represents the economic value, provided that the particular method of changing the transfer numbers considered does not change the cost of the packing.

Fig. 5 is a graphical representation of eqns. (10) and (11), lines of shell resistance, F, and minimum performance coefficient, C, being plotted to co-ordinates of transfer surface and optimum heat-transfer number.

(6) COST FACTORS

To complete the economic design, five cost factors have to be introduced, namely

z_s = Annual capital charges and maintenance costs of packing per square foot of packing surface.

z_A = Annual costs incurred by increasing the horizontal area, A, of the tower by 1 ft², without increasing the total packing surface or the total fan power.

z_F, z_w = Annual costs incurred by increasing the power input rating of the fan or pump motors respectively by 1 ft-lb/sec.

z_H = Annual costs incurred per square foot of A by increasing the height of a natural draught chimney by 1 ft.

Only the relative values of these cost factors need to be known for the economic design of the tower to a given performance specification.

(7) ECONOMIC DESIGN

It is shown in Section 14.2 that the total annual costs (for pumping and air power, maintenance and capital charges) are a minimum for a given tower capability when

(*a*) The packing surface is in accordance with the equation

$$\frac{ks^2}{2} = \frac{F}{f} = \frac{z_A - z_wsw/a\eta_w}{z_s + z_ww/a\eta_w} \quad . \quad . \quad . \quad (12a)$$

$$= Mz_A/z_s \quad . \quad . \quad . \quad . \quad . \quad . \quad (12b)$$

where M is defined by the above equations and has values of about $0\cdot75$ for typical film packings.

(*b*) The fan power or chimney height is in accordance with the expressions

$$p = \eta_F(z_A + z_ss)/2z_F \quad . \quad . \quad . \quad . \quad (13a)$$

$$H = (z_A + z_ss)/2z_H \quad . \quad . \quad . \quad . \quad (13b)$$

From eqn. (12) lines of constant Mz_A/z_s can be added to Fig. 5.

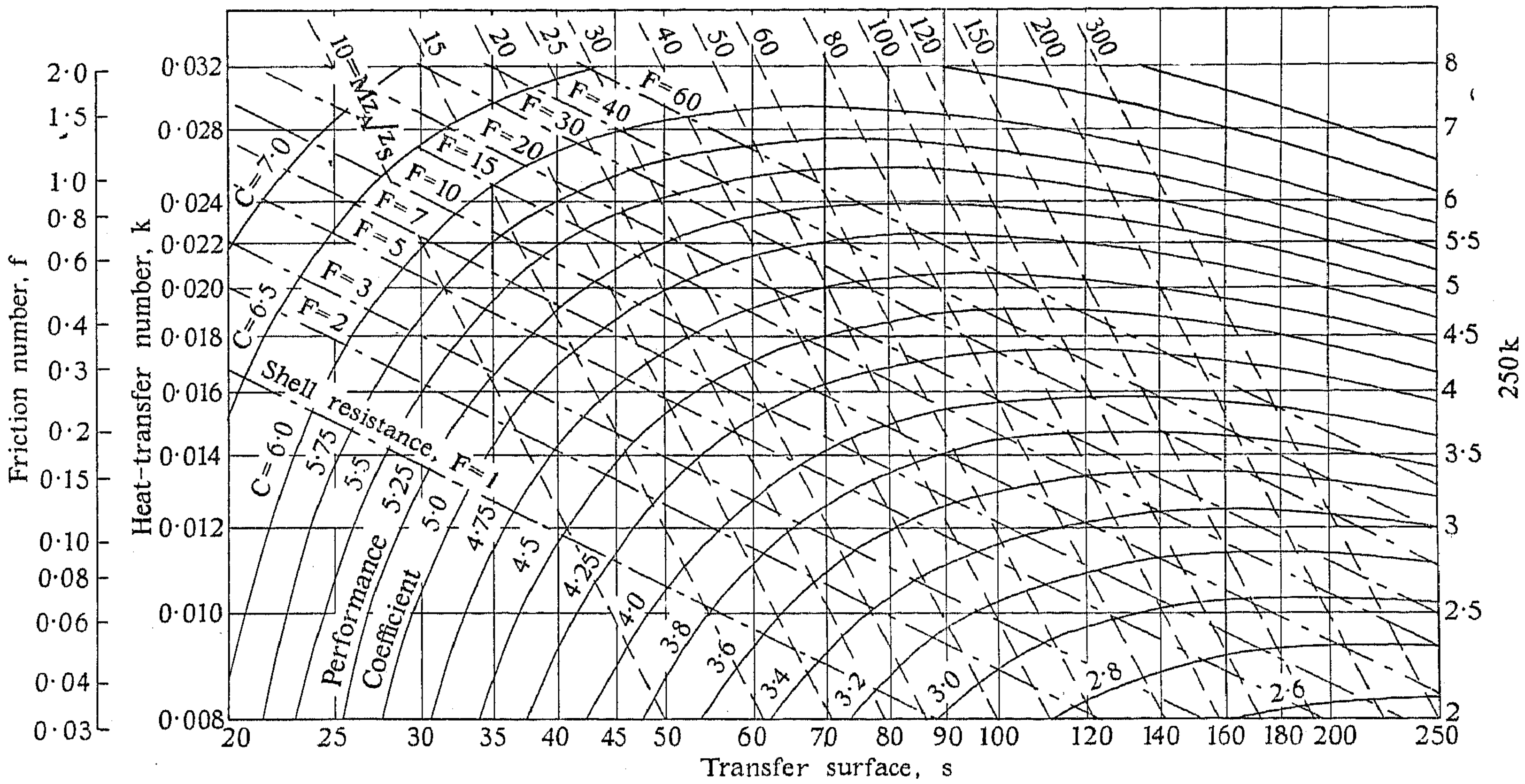


Fig. 5.—Chart for economic tower design.

Plotted from formulae: $Mz_A/z_s = ks^2/2$; $F = 31\,250k^4s^2$; $C = 15{\cdot}8\,(ks^{1/2} + 2s^{-1/2})^{4/3}$; these conform with eqns. (10), (11), and (12*a*) in the text.

Table 2

EXAMPLES OF ECONOMIC DESIGN

Item	Symbol	Amount		
Specified duty				
(*a*) Heat quantity, B.Th.U./sec	$Q = qA$	300 000		
(*b*) Water temperatures, °F	θ_1, θ_2	$\theta_1 = 85$, $\theta_2 = 69$ ($\theta_m = 77$)		
(*c*) Atmospheric temperatures, °F	$t_{w1}\ t_{d1}$	$t_{w1} = 49$ $t_{d1} = 52$		
		Mechanical draught	Natural draught Type I*	Natural draught Type II*
Design data (*from Table* 3)				
(*a*) Shell resistance	F	13	25	16
(*b*) Fan-set efficiency	η_F	0·6	—	—
(*c*) Area cost ratio	z_A/z_s	59	57	73
(*d*) Fan-power cost ratio, sec/ft-lb	z_F/z_s	4·80	—	—
(*e*) Pumping-power cost ratio, sec/ft-lb	z_w/z_s	4·36	4·36	4·36
(*f*) Chimney cost ratio,† ft^{-1}	z_H/z_s	—	0·23	0·29
Design				
Step 1. Estimate the factor M	M	0·71	0·79	0·76
Step 2. Read from Fig. 5, for given F and Mz_A/z_s				
(*a*) Heat-transfer number	k	0·0170	0·0207	0·0162
(*b*) Friction number	f	0·310	0·56	0·265
(*c*) Packing surface	s	70	66	82
(*d*) Performance coefficient	C	4·35	4·85	4·17
Step 3. Obtain from eqns. (13*a*) and (13*b*):				
(*a*) Air power (ft-lb)/sec-ft	p	8·05	—	—
(*b*) Chimney height, ft	H	—	270	270
Step 4. Obtain from Figs. 1 and 2 and eqn. (5) respectively:				
(*a*) Atmospheric factors	y_M, y_N	1·42	10·22	10·22
(*b*) Enthalpy difference, B.Th.U./lb.	$h''_m - h_1$	21·0	21·0	21·0
(*c*) Heat loading, B.Th.U./sec-ft	q	6·82	4·50	5·66
(*d*) Horizontal area (Q/q), ft²	A	44 000	66 600	53 000
Step 5. Check M from eqn. (12*a*)	M	0·70	0·80	0·75
Ultimate chimney selection (from eqn. 26)				
(*a*) Number	N	—	3	2
(*b*) Height, ft	H	—	254	270
(*c*) Diameter, ft	D	—	170	180

* Types I and II represent towers with and without water-collecting troughs respectively.
† This actually varies with height and diameter; see Section 14.3.2.

The economic design of cooling towers may now be carried out using the 5-step procedure illustrated by the worked examples in Table 2. The first step is a trial, i.e. consists in estimating the value of M. The next three steps give all the required cooling-tower design particulars, i.e. the transfer numbers, packing surface, performance coefficient, fan power or chimney height, ground area and water rate. The fifth step is a check of the value of M from eqn. (12a). If this check agreed within 10% with the trial value (as it normally would), the total annual costs given by the trial design would be within about 0·2% of the theoretical minimum and the trial design would be considered satisfactory. If the disagreement were more than about 10%, the procedure would be repeated with the new value of M. The entire sequence can be completed in a few minutes.

The design procedure illustrated by the Table requires a knowledge of only three design factors, namely the shell resistance, F, the area/surface cost ratio, z_A/z_s, and the fan-power/surface cost ratio, z_F/z_s. The values which these design factors attain under various circumstances are discussed in Section 14.3. It is worth noting that a design conforming with eqn. (13a) has capital charges and maintenance costs $(z_A + z_s)$ which are twice as great as the annual costs of the fan power, pz_F/η_F.

(8) INFLUENCE OF LOCAL CONDITIONS

To show more clearly the effect of variations in the design factors on the economic packing surface and transfer numbers, eqns. (12a) and (11) may be combined to give the following expressions:

$$f = F(z_s/z_A M) \quad . \quad . \quad . \quad . \quad . \quad (14a)$$

$$s = 8\cdot 9F^{-1/6}(Mz_A/z_s)^{2/3} \quad . \quad . \quad . \quad (14b)$$

These expressions indicate that low transfer numbers and a high packing surface are economic when the shell resistance is low and the area/surface cost ratio, z_A/z_s, is high. An example would be a small mechanical-draught tower situated on a very expensive site, so that the area/surface cost ratio might be as high as 100 and the shell resistance as low as 8. When M is 0·72 the economic packing particulars become $s = 108$, $k = 0\cdot 0121$, $f = 0\cdot 112$.

An opposite example is a large natural-draught cooling tower. The area/surface cost ratio would then be about 57 and the shell resistance about 25, giving the economic design particulars $s = 66$, $k = 0\cdot 0207$, $f = 0\cdot 56$ as shown in Table 2. The range of variation of the economic friction factors is thus about 0·1–0·5, and several packings should be developed to cover this range adequately.

The most frequent fault in current designs of film packings appears to be the use of high-transfer-number packings for applications where lower transfer numbers would give better results, e.g. where large packing surfaces are employed. A second fault is the offer, for power station applications, of towers in which the fan powers are too high, usually because the makers concerned have been guided by industrial practice, which is normally based on higher ratios between capital charges and power costs. A third example of bad design is the recent installation of a natural-draught tower with a film packing which had a surface only about 50% of that which would have been economic. Faults in design such as these often increase the total annual costs incurred by a cooling-tower installation by more than 10%.

(9) DESIGN OF PACKINGS WITH ABNORMAL CHARACTERISTICS

For packings which do not quite satisfy the approximate general correlation equation (8a), on which the preceding discussion is based, eqn. (8b) containing the correction factor b may be used. For given values of shell resistance, F, and cost ratio, z_A/z_s, the values of k and s obtained from Fig. 5 should then be multiplied by $b^{-1/3}$ and $b^{1/6}$ respectively, while the friction number f remains unchanged. The performance coefficient, C, should be calculated from eqn. (6).

When it is desired to use the more precise relation, eqn. (8c), and sufficient test data are available to permit b_1 and c to be found for the particular type of packing investigated, the optimum heat-transfer number is given by the equation

$$250^{(c-1)}b_1k^cs(cks + 2c - 6) = 6F \quad . \quad . \quad (15)$$

which reduces to eqn. (11) when $b_1 = 1$ and $c = 3$.

The economic packing surface is given by

$$\frac{2(z_s s + z_w sw/a\eta_w)}{3(z_s s + z_A)} = \left[\frac{2}{2 + ks} - \frac{fs}{3(F + fs)}\right] \quad . \quad . \quad (16)$$

These expressions can be used to construct a design chart similar to Fig. 5.* This applies also to packings of the splash-bar type, although different charts may be necessary for different water and air rates. Special techniques avoiding this multiplicity of charts can be evolved for splash-bar packings, but a description of these is outside the scope of the paper.

(10) INFLUENCE OF FLOW RATES AND SCALE DIMENSIONS ON THE TRANSFER NUMBERS

While the geometric shape of the packing is the controlling factor for the transfer numbers of film packings, three secondary factors can also be significant. These are the water rate, w, the air rate, G, and the "scale dimension," d, the latter being defined in the paper as $4A$/(perimeter of air-flow path).

Theoretical considerations indicate that the effect of these three factors can be expressed approximately in terms of two groups, namely the specific water loading wd and the air-flow Reynolds number, Gd/μ. With a specific water loading of 0·12lb/sec-ft and a Reynolds number of 10 000 as typical reference conditions, the transfer numbers in the main range of interest can be represented by the expressions

$$k = k_x(wd/0\cdot 12)^m(Gd/10\,000\,\mu)^{-n} \quad . \quad . \quad (17a)$$

$$f = f_x(wd/0\cdot 12)^{mf}(Gd/10\,000\,\mu)^{-nf} \quad . \quad . \quad (17b)$$

The condition that the k/f correlation, eqn. (8a), shall not be affected by variations in w, G or d is then that $3n = 3m = n_f = m_f$. When this condition is satisfied, moderate variations in any of these three factors will not produce sensible changes in the performance coefficient of cooling towers designed to suit eqn. (11), since $\partial C/\partial k = 0$ at the optimum design point. Experimental evidence suggests that large variations in these three factors produce only very small changes in the performance coefficients of towers with film packings. For very low values of the specific water loading, incomplete wetting of the packing would, however, be obtained and the performance coefficient might then increase materially.

For many practical purposes only the influence of flow rates is of interest. With 0·36lb/sec-ft² as a representative condition, eqns. (17a) and (17b) may be rewritten

$$k = k_0(w/0\cdot 36)^m(G/0\cdot 36)^{-n} \quad . \quad . \quad . \quad (18a)$$

$$f = f_0(w/0\cdot 36)^{mf}(G/0\cdot 36)^{-nf} \quad . \quad . \quad . \quad (18b)$$

The six packing constants appearing in the right-hand side of these expressions completely define the values of the transfer

* Use eqn. (15) to construct k/F curves for given values of s; from this plot F lines on the k/s chart. Calculate f from eqn. (8c), then add lines of constant C from eqn. (6) and lines of z_A/z_s from eqn. (16) for given value of w.

numbers over the practical range of operating conditions, and the ratio

$$R = 250k_0/(250f_0)^{1/3} \quad . \quad . \quad . \quad . \quad . \quad (19)$$

may be regarded as a figure of merit of the packing. It would be unity for a packing satisfying the general correlation equation (8*a*) at the reference flow conditions, and less than unity for inferior packings.

Since the viscosity of air is about $1 \cdot 2 \times 10^{-5}$lb/sec-ft, eqns. (17) and (19) become identical when $d = 1/3$ ft and $k_x = k_0$, $f_x = f_0$.

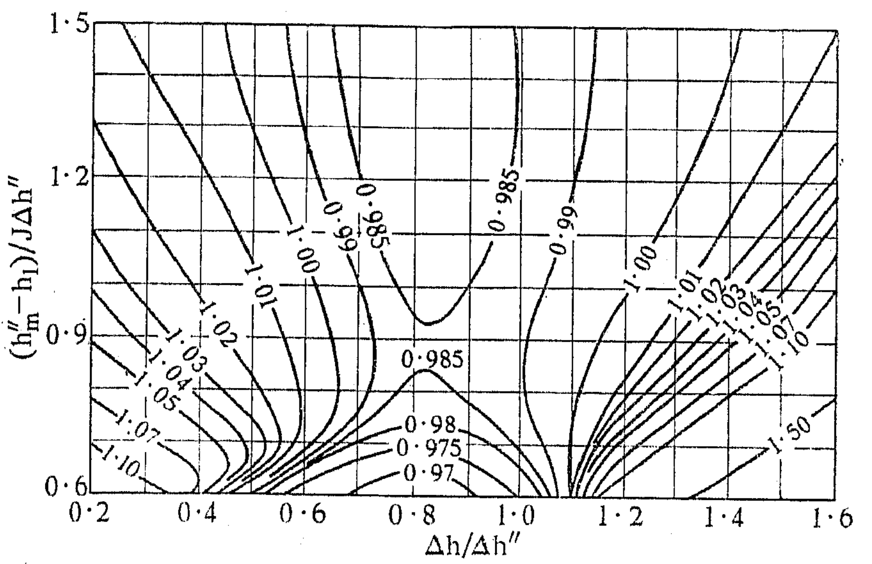


Fig. 6.—Distribution factor for contra-flow cooling tower.

Drawn for $h_1 = 11$ B.Th.U./lb, $\Delta\theta = 18°$ F. For lower values of h_1 and $\Delta\theta$, J is slightly greater than shown by chart; for higher values of h_1 and $\Delta\theta$, J is slightly smaller.

Test data given in Reference (10) suggest that the values of m are about $0 \cdot 3$ in the region of interest.

(11) CONCLUSIONS

The representation of the performance of a cooling tower by a single coefficient, C, greatly facilitates the designer's task. In the paper it has been shown how that coefficient can be used to determine the optimum compromise between the friction and heat-transfer properties of the packing. For precise results the work should be supported by an experimental k/f correlation for the particular type of packing used, but for most purposes the approximate general correlation on which the design chart, Fig. 5, is based, gives results of sufficient accuracy. This chart makes it possible to determine the economic values of the packing constants, packing surface and performance coefficient by inspection. With its aid economic tower designs can be completed rapidly, as illustrated by the worked examples.

Adoption of the recommendations made in the paper would result in each cooling-tower maker developing several packings covering a range of friction numbers from $0 \cdot 1$ to $0 \cdot 5$ for different applications. Large natural-draught towers without water-collecting troughs would, for instance, have packings with relatively high transfer numbers. Natural-draught towers on expensive sites would have low heat-transfer numbers, large packing surfaces per unit ground area and relatively low shell resistances.

(12) ACKNOWLEDGMENTS

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(14) APPENDIX

(14.1) Accuracy of Approximations

(14.1.1) Integration of Heat-Transfer Equation.

The exact form of the contra-flow cooling-tower heat-transfer equation is

$$ks = \int_1^2 \frac{1}{h'' - h} dh = \frac{j\Delta h}{h''_m - h_m} = \frac{j'\Delta h}{h''_e - h_m} \quad . \quad (20)$$

where j and j' are distribution factors defined by this equation, and

$$h''_e = \frac{1}{\Delta\theta}\int_1^2 h'' d\theta$$

The exact contra-flow expression for the left-hand side of eqn. (1) is therefore

$$(h''_m - h_m)/J \text{ or } (h''_e - h_m)/J'$$

where $$J = \frac{(h''_m = h_m) + (h_m - h_1)}{(h''_m - h_m)/j + (h_m - h_1)}$$

and $$J' = \frac{(h''_e - h_m) + (h_m - h_1)}{(h''_e - h_m)/j + (h_m - h_1)} \quad . \quad (21)$$

The approximation made in the paper [eqn. (4)] is that $J = 1\cdot 0$, whereas its actual values are usually in the range of $0\cdot 98$–$1\cdot 03$, as illustrated by Fig. 6. The approximation made by Merkel was that $J' = 1\cdot 0$, whereas its actual values are usually between $1\cdot 01$ and $1\cdot 05$. The two approximations, therefore, have comparable accuracies, and the first has been chosen mainly on the grounds of simplicity. It was first used by Kennedy and Margen.[4]

Fig. 6 is drawn for a particular wet-bulb temperature and cooling range, and varying values of all other factors. To represent J under all conditions a large number of charts would be required, since the exact solution of the heat-transfer equation relates five variables, i.e. q, h_1, h_2, h_1'' and h_2''. Such charts could be constructed from the book of graphs referred to by Lichtenstein.[5]

(14.1.2) **Atmospheric Factors.**

(*a*) *Mechanical-draught towers.*—The values of y_M shown in Fig. 1(*a*) are based on the assumption that the effective average air temperatures inside the packing are as follows

Wet-bulb temperature, $t_{wm} = (t_{w1} + 10)°$ F
Dry-bulb temperature, $t_{dm} = \frac{1}{2}(t_{w1} + t_{d1}) + 10°$ F

If t_{wm} were 5° F larger than the value assumed (corresponding to about 50% increase in the heat loading or performance coefficient) the increase in y_M would only be $0\cdot 8$%. It will be understood from this that the chart is sufficiently accurate for practical purposes, but if desired a correction can be applied after the design has been completed and the actual temperature rise of the air inside the tower has been obtained.

(*b*) *Natural-draught towers.*—The values of y_N shown in Fig. 1(*b*), have been calculated from Chilton's chart for the function $f(t_{w1}, t_{d1})$ using the conversion $y_N = (3\,600^2/f(t_{w1}, t_{d1}))^{1/3}$. Chilton's chart is based on the assumption that the exit air is saturated (which does not lead to appreciable errors, except in very dry climates) and that $H/(F+fs)$ and q have specific values. Practical variations in these parameters do not, however, produce appreciable changes in the true values of y_N.

(14.1.3) **Reynolds Analogy.**

The Reynolds analogy, $k = f/2$, would apply exactly for the ideal packing only if:

(*a*) The thermal diffusivity of air and the diffusivity of water vapour through air were numerically equal to the kinematic viscosity of air.

(*b*) The temperature drop across the water film were negligible.

Actually, the diffusivities are slightly greater than the kinematic viscosity, which tends to make k about 7% greater than $f/2$. On the other hand, the temperature drop across the water film is equivalent to a reduction in k, so that the net result should be fairly close to the Reynolds analogy.

(14.2) Conditions for Minimum Costs

Let Z be the total annual costs incurred by operation of cooling tower (i.e. cost of power, maintenance and capital charges) and suppose that the total air power Ap (or the product AqH in the case of natural draught) is constant.

Then Z will attain a minimum for a given tower capability when

$$\frac{A\partial(h_m'' - h_1)/\partial A}{s\partial(h_m'' - h_1)/\partial s} = \frac{A\partial Z/\partial A}{s\partial Z/\partial s} \quad . \quad . \quad . \quad (22a)$$

i.e. when

$$\frac{2/3}{2fs/3(F+fs)} = \frac{A(z_A + z_s s)}{As(z_s + z_w w/a\eta_w)} \quad . \quad . \quad (22b)$$

Rearranging:

$$\frac{F}{f} = \frac{z_A - z_w sw/a\eta_w}{z_s + z_w w/a\eta_w} \quad . \quad . \quad . \quad . \quad (22c)$$

When this is combined with eqn. (11), eqn. (12) for the economic packing surface is obtained.

The term $z_w w/a\eta_w$ in these expressions represents the increase in the pumping costs when unit increase in the packing surface s is obtained by raising the height of the packing.

If now s is maintained constant and the air power, p, or chimney height, H, is varied, Z will attain a minimum when

$$\frac{A\partial(h_m'' - h_1)/\partial A}{p\partial(h_m'' - h_1)/\partial p} = \frac{A\partial Z/\partial A}{p\partial Z/\partial p} \quad . \quad . \quad . \quad . \quad (23)$$

(14.3) Design Constants

This Section gives data for assessing the three factors which are regarded as design constants in the text, i.e. the shell resistance, F, and the cost ratios, z_A/z_s and z_F/z_s.

(14.3.1) **The Shell Resistance.**

The shell resistance has three components, F_1, F_2 and F_0, which are caused respectively by the resistance of the inlet, the resistance of the outlet and the resistance of internal obstructions such as the water distribution system.

It is known from tests on models that when r_1, the area of the shell inlet per unit A, is very small, i.e. of the order of 1/600, the inlet loss is approximately $(1/r_1)^2$, i.e. corresponds to the total loss of the kinetic energy at the area of the inlet. For values of r_1 in the practical range, however, i.e. $1/6$–$1\cdot 0$, the smallest effective area of the flow path is often not the inlet itself, but the *vena contracta* which forms just beyond the inlet. The inlet resistance may then be represented by e/r_1^2, where e is a factor which can attain values as high as $2\cdot 5$ for unbaffled towers.

To maintain a low inlet resistance, r_1 should be large, i.e. the air inlet height, H_1, should be large. With film-type packings in particular this involves raising the level of the packing and consequently increases the pumping costs (unless tray water-collecting systems are used). Obviously there is an economic compromise between an unduly high inlet resistance and excessive pumping costs. If e is constant and the bottom of the packing is at the level, H_1, of the top of the air inlet, the economic compromise is given by

$$H_1 = \left[\left(\frac{D_1^2 e\eta_w}{16wz_w}\right)\left(\frac{z_s s + z_A}{F+fs}\right)\right]^{\frac{1}{3}} \quad . \quad . \quad . \quad (24a)$$

which reduces to

$$H_1 = 0\cdot 373\left(\frac{\eta_w e D_1^2 z_A}{wFz_w}\right)^{\frac{1}{3}} \quad . \quad . \quad . \quad . \quad (24b)$$

if $M = 0\cdot 7 = F/fs$, which represents a typical film-packing condition. From eqn. (24*b*) the inlet resistance becomes

$$F_1 = 0\cdot 448e^{\frac{1}{3}}\left(\frac{wD_1Fz_w}{\eta_F z_A}\right)^{\frac{2}{3}} \quad . \quad . \quad . \quad . \quad (25)$$

To apply these expressions to mechanical-draught towers, the inlet diameter D_1 should be replaced by $2B$, where B is the width of one cell, i.e. the spacing between the two walls containing the air inlets.

The value chosen for the fractional shell-outlet area, r_2, represents a compromise between the desire to produce a low outlet resistance and low shell costs. This choice is influenced by the value of the total tower resistance, $F+fs$, since the fractional improvement in the performance coefficient obtained by reducing any resistance component by one velocity head is $1/[3(F+fs)]$. The collecting-trough design has a lower value of $(F+fs)$ than the conventional design, and consequently there is a greater financial incentive to increase the fractional shell outlet area.

Table 3

TYPICAL TOWER DESIGN DATA
(Film-Type Packings)

Item	Symbol	Tower: Mechanical draught	Tower: Natural draught, Type I*	Tower: Natural draught, Type II*
Leading dimensions				
Chimney diameter, ft	D	—	180	180
Chimney height, ft	H	—	270	270
Width of cells, ft	—	36	—	—
Height of air inlet, ft	—	11	19	28
Shell resistances				
Inlet component†	F_1	6·6	14·3	6·4
Outlet component	F_2	2·9	7·2	4·6
Internal component	F_0	3·5	3·5	5·0
Total	F	13·0	25·0	16·0
Relative costs‡				
Packing-surface costs	z_s/z_s	1·0	1·0	1·0
Area costs				
(*a*) Land	—	4	3	3
(*b*) Basin	—	13	11	12
(*c*) Water distribution	—	10	10	10
(*d*) Water collection	—	—	—	10
(*e*) Shell or chimney	—	18	33	38
(*f*) Initial component of fan and control gear	—	14	—	—
(*g*) Total	z_A/z_s	59	57	73
Incremental chimney height cost, ft^{-1}	z_H/z_s	—	0·23	0·29
Power costs ft-sec/lb.				
(*a*) Power tariff		1·7 + 4·8 × load factor		
(*b*) Power component of fan or pump charges		0·5		
(*c*) Total	z_F/z_s	2·2 + 4·8 × load factor		

* Types I and II represent towers without and with water-collecting troughs respectively.
† Based on $e = 2·5$.
‡ A typical present-day value of z_s would be £0·0045/ft²/annum. With this value the power tariff corresponds to £5·6/kW/annum, plus 0·44d./kWh. These values (plus the power component of the fan or pump charges) are used in Table 4.

(14.3.2) **Capital Charges and Maintenance.**

Table 3 shows the manner in which the cost factors can be estimated. In allocations of the charge for land, allowance has to be made for the fact that mechanical-draught towers have to be arranged in long rows of narrow cells to give adequate air access and that no obstructions must be erected near the sides of the tower. Hence a bigger site area per unit A is usually required than with natural-draught towers. With the latter type, however, the actual ground area is usually some 14% larger than the area, A, at the packing level.

The cost of the chimney is a complex function of the height and the diameter at various levels. It is known, however, that it is more economic to increase the number of chimneys than their dimensions once a height of about 270 ft and a packing-level diameter of about 180 ft are exceeded. With this knowledge large natural-draught cooling-tower installations can be designed quickly, using the sequence given in Table 2.

If the economic horizontal area of the total installation does not correspond to an integer number of chimneys of height 270 ft and diameter 180 ft, the nearest integer should, of course, be chosen, and the revised height and diameter be estimated from the expressions

$$H = 270(A/25\,500)^{1/3} \quad . \quad . \quad . \quad . \quad (26a)$$

$$D = 180(A/25\,500)^{1/3} \quad . \quad . \quad . \quad . \quad (26b)$$

For the economic design of small natural-draught towers a knowledge of the precise variation of z_A and z_H with H and D is necessary. In such cases slightly larger height/diameter ratios are found to be economic.

(14.3.3) **Power Costs.**

In assessing the air- and pumping-power costs, z_F and z_w, the appropriate load factors, L_F and L_w, should be used. With power stations, L_w is usually slightly larger than the station load factor, L, because sets are normally supplied with the full-

Table 4

COST COMPARISON

Item	Mechanical draught	Natural draught: Type I	Natural draught: Type II
Initial components of pumping head (= H_1 + 2), ft	13	21	5
Packing component of pumping head, ft	4·7	4·4	5·5
Total tower pumping head, ft	17·7	25·4	10·5
Pumping costs, £/annum	8 100	11 700	4 800
Capital charges and maintenance, £/annum	25 500	36 900	36 900
Fan-power costs, £/annum	12 800	—	—
Total cost, £/annum	46 400	48 600	41 700

load water quantity whenever they are running. Air-power load factors are still higher, because it does not pay to cut out cells* until light heat loadings are reached. The load factors selected for the examples are $L = 0\cdot40$, $L_w = 0\cdot45$ and $L_w = 0\cdot54$.

(14.4) Cost Comparison

Table 4 compares the costs of the three designs using the data given in Tables 2 and 3. The Table should not be taken as a complete indication of the relative merits of mechanical and natural draught, since the partial load performances of these units differ. Moreover, the figures do not allow for the recirculation of some warm exit air experienced with most mechanical-draught towers under some wind conditions. More detailed comparisons are made in Reference 13.

It is evident from the figures that film-type packings offer little promise with large natural-draught towers unless water-collecting troughs are used to avoid the pumping costs otherwise introduced by the exceptionally large clearance height.

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE SUPPLY SECTION, 5TH JANUARY, 1955

Mr. F. H. S. Brown: Messrs. Kennedy and Margen tackle a problem which bristles with variables and practical difficulties. The paper establishes the logic of a trend towards smaller cooling towers and associated higher circulating-water temperatures and therefore back-pressures. I entirely agree with the logic of the trend so established, but I am not so happy about some of the precise arithmetical values given to some of the figures in the paper. In order to render the general problem capable of generalized mathematical treatment the authors have been compelled to average some of the variables involved. While I agree that this is permissible in order to establish a general trend, I do not think that it is possible to apply precise mathematical values to the trend thus established, i.e. no deduction can be more accurate than the assumptions made in its calculation.

For instance, Fig. 2 of the paper shows the load distribution assumed over a year for power stations run at various load factors, and it will be seen that, for instance, in (*b*) 2-shift running is assumed even in the winter for a station with a load factor as high as 45%. That may well be so in some cases, but it will not, I suggest, hold in every case. This is of some importance, because Table 2 gives the assumed mean atmospheric temperatures with which assumed load curves are associated. Are these assumed atmospheric temperatures 2-shift averages (15h/day) or 3-shift averages (24h/day)? This is important, because the atmospheric temperature, upon which, of course, the performance of the cooling tower depends in the long run, can vary by as much as 6°F according to whether the 15h or the 24h average is taken.

Similarly, Table 4 gives a cost comparison for a station designed on the basis of a reduced cooling-tower capacity and shows a saving in favour of the new design of £16 900 per annum. It is interesting to note, however, that that saving is comparable with, and in fact slightly less than, the additional cost of £22 000 per annum given as the adverse effect of the lower vacuum on the economics of the station. The similar order of these figures is, I suggest, important, in that the net saving is the difference between a fairly large loss due to reduction in vacuum and the extent to which it is recouped by savings in pumping costs and in capital costs. The calculation assumes in the footnote that the same condenser will be used in both cases. However, since the effect of vacuum is in itself larger than the overall saving, I think it essential that the marginal differences in condenser performance which will occur under the postulated conditions should be taken into account.

The authors suggest that the terminal temperature difference of $7\frac{1}{2}$°F at the hot end of the condenser will apply in both cases, in spite of the fact that the water quantity through the condenser is reduced in the ratio of $1\cdot55:1$. If in a given condenser the water velocity is reduced in that ratio, the velocity of water through the tubes will be reduced and the heat-transfer coefficient will also be reduced, so that the terminal temperature difference cannot be assumed to remain constant at $7\frac{1}{2}$°F: there will be a significant difference between the two cases. Alternatively, if a condenser is designed to maintain the same heat transfer coefficients, i.e. the same velocity in the tubes, the pumping power involved will not vary as stated in the paper, and therefore the credit item of savings in pumping power will not attain the value stated in the paper.

These points are important, because marginal differences in the performance of the turbine and condenser combination become extremely important when the net value of the alteration in design is of the same order as the differences in performance obtained by the change in design. Thus I cannot agree with the statement in Section 7 that the charts permit the choice of economic cooling-tower data with an accuracy sufficient for practical purposes. The charts are an advance on anything which I have seen of a similar nature, but I do not think that they provide a royal road to the exact solution of this involved problem. It will, I fear, remain necessary in a practical case to perform a laborious series of calculations in any particular instance before the exact solution can be obtained.

Coming from the particular to the general there are two points which I should like to make. First, the paper accepts the exhaust heat loading as one of the parameters of this problem. I feel that the authors are entirely correct in doing this. It could be argued with considerable logic that the turbine exhaust and condenser and cooling-tower circuits are indissolubly linked, and that, if a change is to be made in the cooling-tower circuit which affects the vacuum, a corresponding change should also be made in the design of the turbine exhaust. In my view, however, there is little doubt that the authors are quite right in not assuming any such thing. I feel that the large turbine exhaust always pays, and that having deduced that increased circulating water temperatures may be an economic proposition, the authors are correct in not stating that lower vacua would justify a reduction in turbine exhaust area, which might superficially appear to be the next logical step.

Secondly, I heartily concur with the authors when they emphasize the value of natural river cooling to the power stations of this country. The cooling capacity of our rivers is a national asset in precisely the same way as deposits of coal, iron ore, etc., and I think that they should be exploited to the maximum permissible extent. I appreciate that every individual and every corporate body in this country has a public duty not to spoil any of our natural amenities, but I am certain that the cooling capacity of the rivers can be made use of without destroying any of those amenities. The history of our rivers has to some extent been unfortunate, and many have been spoilt by industrial effluents of one sort or another, although not usually by the electricity supply industry. There is a real danger, however, that crippling requirements will be imposed upon the industry to avoid any danger, or any suggested danger, of spoiling the amenities of the rivers, and imposed, if we do not exercise watchfulness, to a quite unnecessary degree.

* Except when the towers contain water-distribution systems which become inefficient at low water rates.

Mr. H. Chilton: The paper by Mr. Margen is open to the criticism that the numerical correlation between the heat transfer number and the friction number on which it is based is not justified by the experimental data plotted in Fig. 4. We will not be able to apply the friction-heat transfer correlation to full advantage until further experimental results become available. In the meantime the paper clarifies the lines on which future experimental work should be conducted and analysed. Many of the economic relationships developed do not depend on the friction-heat transfer correlation, and these will be of immediate value.

From the point of view of the practical designer the only objection to the design procedure demonstrated in Table 2 is that it involves redesigning the packing for practically every new tower, and it is pertinent to inquire whether the savings in cost resulting from using the most economic packing arrangement would justify the additional design and production cost implied by this.

Table A compares the annual operating costs of towers, Z/z_s, with economic packing, E, with comparable towers of economic optimum design, except that an arbitrary standard packing, S, is used. The Table covers a fairly wide range of design conditions, represented by the cost ratio z_A/z_s. The calculations were based on the example for a mechanical-draught tower in Table 2 of the paper in the following respects:

(*a*) Column 3 is identical with that example except for minor discrepancies which arise from calculating all the derived quantities from the original formulae instead of picking them off the design chart.

(*b*) In all the columns of Table A the unspecified design data are the same as in the worked example.

(*c*) The total annual costs, Z/z_s, are computed on the assumption that the cost ratios are independent of tower size.

The arbitrary standard packing is taken as identical with the economic packing when the cost ratio z_A/z_s is 59 (column 3). Consequently, the standard packing is uneconomic when z_A/z_s is 33·4 (columns 1 and 2) or 111 (columns 4 and 5). This is confirmed by the calculation, but the actual economies resulting from using the economic packing arrangement (0·42% and 0·82% respectively) are small and it is doubtful whether they justify the cost of redesigning the packing.

Table A

EFFECT ON TOTAL ANNUAL COSTS OF USING ECONOMIC PACKING

Column	1	2	3	4	5
z_A/z_s	33·4		59·0	111	
Packing	E	S	E and S	E	S
k	0·0200	0·0170	0·0170	0·0140	0·0170
f	0·4998	0·3069	0·3069	0·1714	0·3069
F	13	13	13	13	13
s	51·00	58·00	70·50	104·1	87
A	58 190	53 620	43 880	31 720	35 160
$Z/z_s \times 10^{-3}$ ..	7 723	7 755	9 012	10 960	11 050
Economy ..	0·42%			0·82%	

The above calculation suggests that, provided we choose a standard packing in such a way that its properties are economic at about the middle of the practical range of design variables, we can probably use it over a fairly wide range of conditions without serious sacrifice in overall economy.

Mr. G. J. Williamson: It is of interest to plot on Fig. 4 of Mr. Margen's paper other data for film-flow packings, taken from Reference 12 (see Fig. A). There is a considerable scatter over a range of 1·6 : 1, in spite of similarity in the geometrical

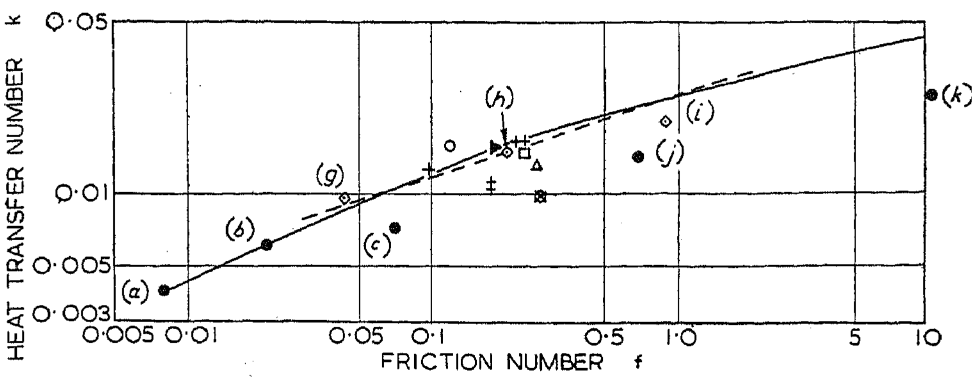

Fig. A.—Friction/heat-transfer correlation.

	Pitch	Depth	Thickness	
	in	in		
⊙	1	1	$\frac{1}{16}$	Plain grids
+	1	2	$\frac{1}{16}$	Plain grids
△	1	1	$\frac{1}{4}$	Plain grids
⧺	1	2	$\frac{1}{4}$	Plain grids
⊗	4	4	$\frac{1}{2}$	Serrated grids
⋕	2	2	$\frac{3}{8}$	Serrated grids
⊡	$1\frac{1}{2}$	$1\frac{1}{2}$	$\frac{3}{16}$	Serrated grids
▶	Average of all tests on cooling towers with 2 in × 2 in × $\frac{3}{8}$ in grids.			

shape of the packings, which shows that the correlation proposed can be regarded only as a very rough approximation. There are practical reasons for the scatter, and these, in effect, limit the choice of packing. For instance, although thin laths give the best transfer/pressure-drop characteristics, it is impossible to use timber laths $\frac{1}{16}$ in thick; but timber is essential for its cheapness. Again, spacing the laths closer than $1\frac{1}{2}$ in would give rise to difficulties due to dirt build-up with normal cooling-tower waters, whereas 4 in-pitch laths give a poor performance owing to lack of adequate water spread. In our experience 2 in-pitch laths $\frac{3}{8}$ in thick have shown themselves to be a useful practical compromise for all water-cooling tower duties. Mr. Margen's approach to the choice of packing is to calculate from the cooling duty and cost data the economic point on the k/f curve; this defines the required packing characteristics but not the physical form of the packing. In theory, the packing has then to be devised so as to give the required characteristics; in practice, a manufacturer is recommended to carry three types of film-flow packing to cover the range of f values from 0·1 to 0·5. I suggest that factors such as the reduced costs arising from standardiza-ion and the practical limitations mentioned above will justify a manufacturer in concentrating only on one design of film-flow packing.

Film-flow packings are finding increasing use in mechanical-draught cooling towers, and particular interest lies in a comparison with splash packings. Mr. Margen mentions that his method of analysis can be applied to splash packings. Preliminary information on performance data on splash packings is shown in Fig. B. Data on the widely used 2 in × 2 in × $\frac{3}{8}$ in serrated grids and on a tower with no packing are given for comparison. The data on splash packings apply for a range of packings used by various cooling-tower manufacturers. The method of plotting correlates all the data, which shows that, for a given expenditure in air-pressure drop, a given volume transfer coefficient is achieved independent of the type of splash packing. (The air-velocity lines, shown dotted, apply only to one particular splash packing; a different set of dotted lines obtains for each packing.) This method of correlation, which is quite empirical, should permit a neat mathematical solution of the economic comparison between grids and splash packings. The general issue is simply that whereas film-flow packings have the advantage in giving a higher heat-transfer rate per unit pressure drop than splash

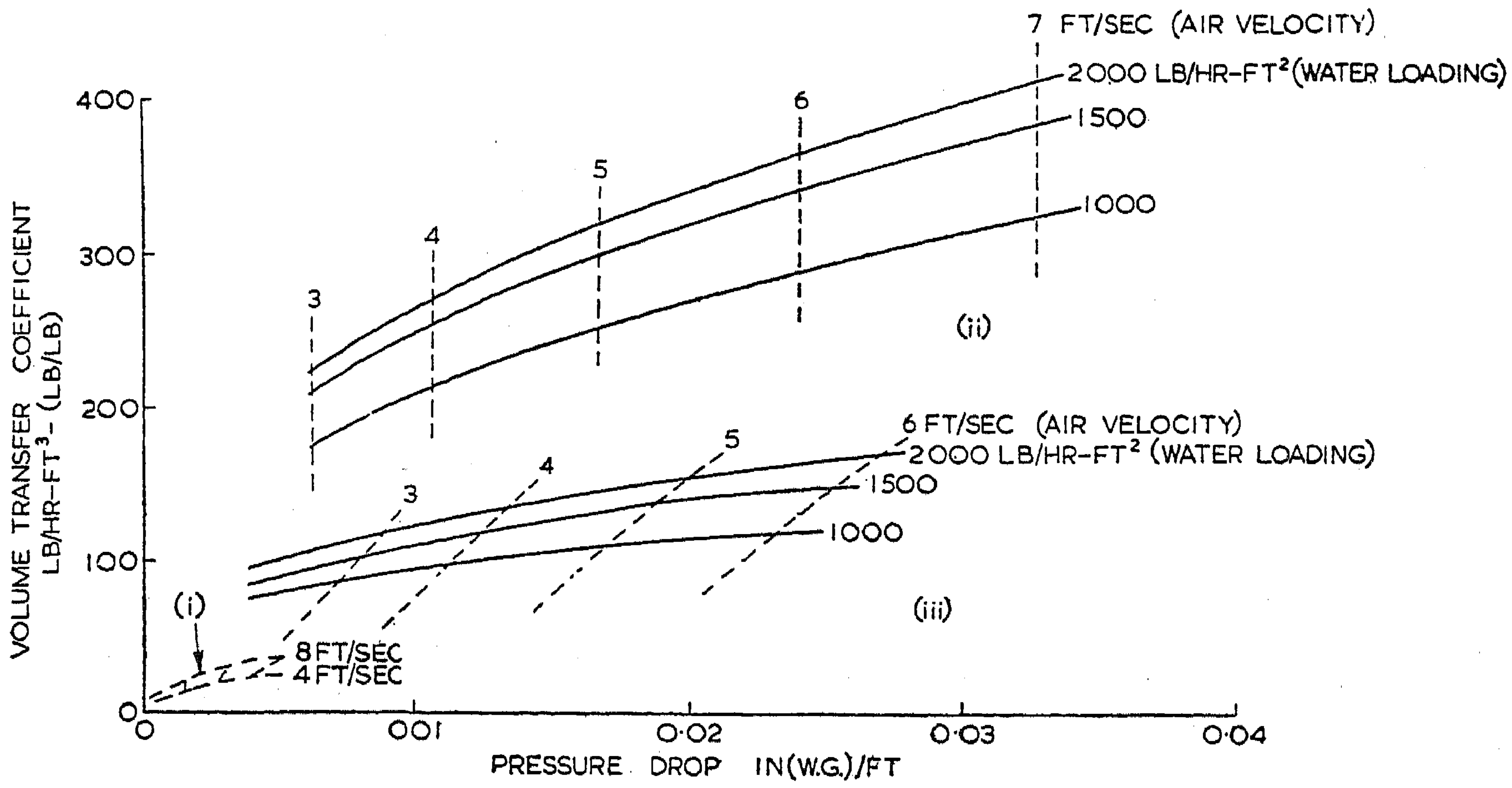

Fig. B.—Packing characteristics.

(i) Spray.
(ii) Serrated grids.
(iii) Splash packings.

packings, they have the disadvantage of requiring more timber to do it. It is hoped that more published data on packing characteristics will become available in the future in order to explore the question further.

Mr. B. Donkin: Messrs. Kennedy and Margen deal with the application of cooling towers in temperate climates: I want to say a few words about the application under tropical conditions. Fig. C shows the economic mean cooling-tower temperature difference for stations operating at 50% annual load factor plotted against the average atmospheric wet-bulb temperatures for the same relative humidities as those assumed for Fig. 7 of the paper. It will be seen that, as the temperature increases, the closer do the water temperatures approach the atmospheric wet-bulb temperature, and in consequence the more favourable is the economic case for cooling towers as opposed to schemes of river cooling.

The reasons for the shape of the curve are as follows. In hot climates heat can be extracted at a greater rate per unit water surface and unit cooling-tower temperature difference than in cold climates. Secondly, the hotter the climate the greater is the gradient of the curve connecting turbine efficiency with vacuum or temperature.

I should like to illustrate that remark by one example, that of an existing power station in Rangoon. The station is cooled by taking water from the Rangoon river, where there is ample water, but it has several serious disadvantages. The first is that the temperature of the river water is about 85°F all the year round, and the second is that the water carries a large amount of fine mud in suspension, and, unless care is exercised, this will be deposited in awkward places in the circulating-water system. Thirdly, the river has a tidal range of over 20ft. Fourthly, the suspended mud deposits itself on the foreshore of the power station, with the result that the river is receding from the power station at a rate of about 10yd per annum. Fortunately, this last point was foreseen, and the river cooling-water-intake works were installed a mile upstream, where the course of the river is stable; but that, of course, increases the pumping costs.

A recent investigation has shown that in Rangoon the average wet-bulb temperature is some 7°F lower than the average river-water temperature. This margin will make it possible to use a cooling tower which will give the station a thermodynamic efficiency not lower than it has at the moment with river-water cooling, and will also obviate all the disadvantages of the existing river-water cooling system.

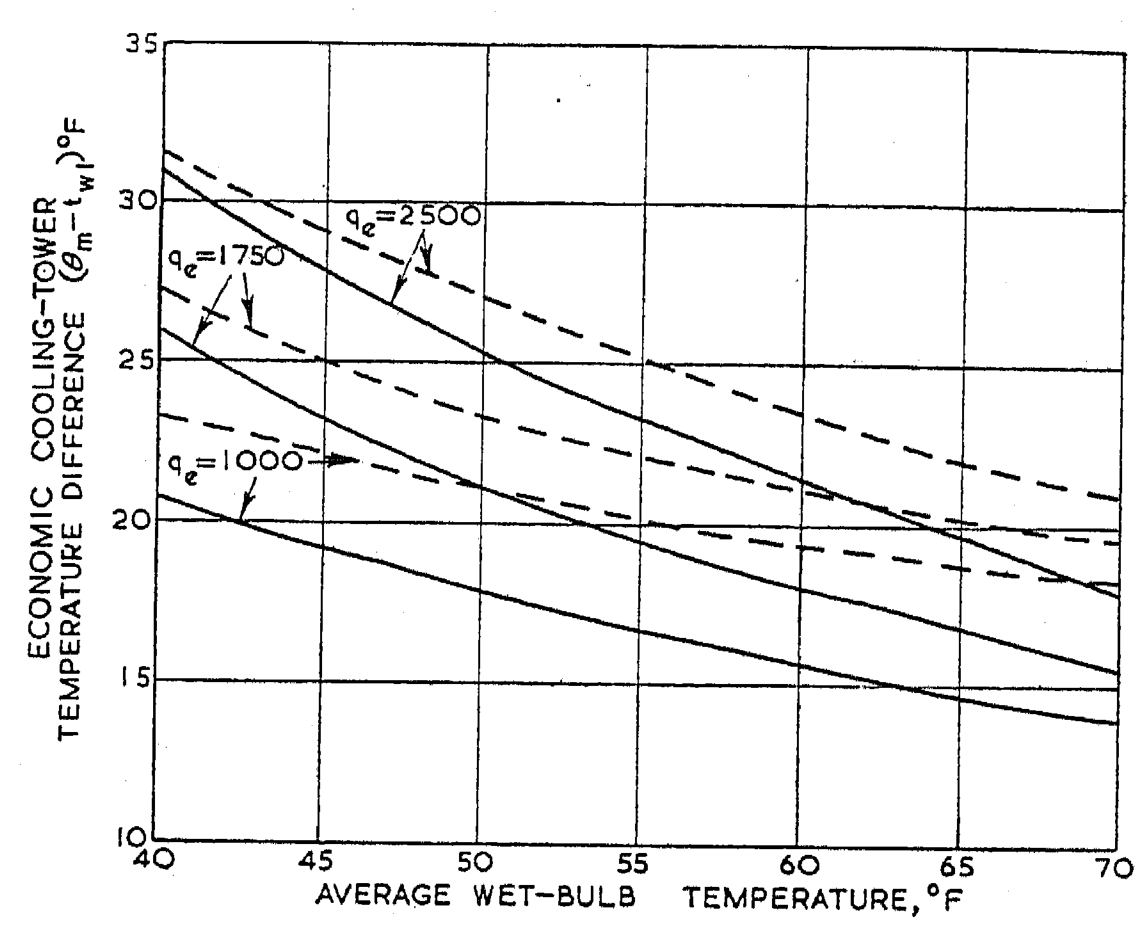

Fig. C.—Influence of climate on economic cooling-tower temperature difference.

It is assumed that dry-bulb temperatures of 41°, 53°, 65° and 78°F are associated with wet-bulb temperatures of 40°, 50°, 60° and 70°F respectively.

——— Mechanical-draught towers.
— — — Natural-draught towers.

Mr. H. J. Lowe: In demonstrating how cooling-tower theory may be extended to the estimation of economic designs, Mr. Margen has made a valuable contribution to the subject.

Measurements of the friction/heat-transfer characteristics of three arrangements of corrugated asbestos sheets have been made in the B.E.A. experimental tower. The arrangements were similar to (*g*), (*h*) and (*i*) in Fig. 3, the latter being an extreme case in which the corrugations were 180° out of alignment. The corresponding friction and heat-transfer numbers at typical water and air rates are: (*g*) 0·041 and 0·0088; (*h*) 0·231 and 0·0143; and (*i*) 0·820 and 0·0190. These results are in very fair agreement with the correlation proposed in Fig. 4. It does not, of course, necessarily follow that if, say, the spacing of each arrangement was progressively changed the same correlation would hold.

It is unfortunate that the total amount of experimental data presently available on the friction/heat-transfer characteristics of cooling-tower packings is so small, and this necessarily limits the confidence which can be placed in the proposed general correlation and in the equations and charts deduced from it. I feel that it will be essential to establish the characteristic for any particular type of packing before using the theory given in Mr.

Margen's paper; this is but a minor inconvenience and does not detract from the value of his work.

Some caution will still be necessary when dealing with large natural-draught towers, because the basic theory assumes simple counter-flow conditions, whereas in fact there is a very complex combination of cross-flow and counter-flow throughout the transfer region. This is illustrated in Fig. D, which shows the

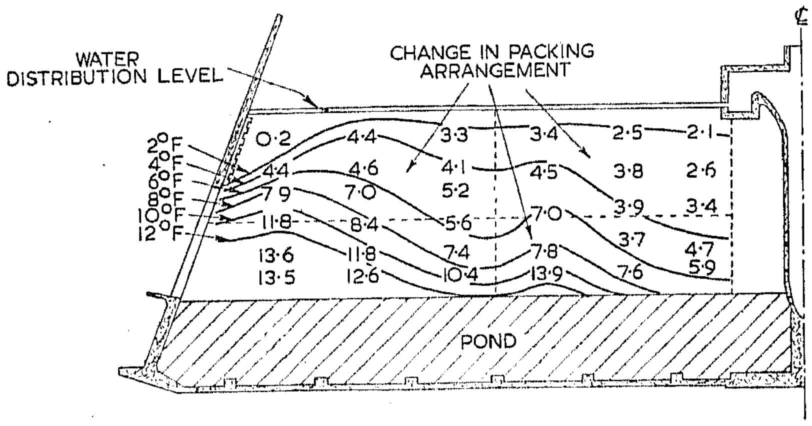

Fig. D.—Water-temperature distribution in terms of cooling range.
All figures indicate cooling, in degrees Fahrenheit, relative to the inlet temperature.

measured water-temperature distribution across a radial section of a tower. A particularly striking feature is the large volume of packing close to the wall which contributes virtually nothing to tower performance, simply because there is no air passing through it. It would therefore appear that, having decided upon the optimum design of packing, there is still considerable scope for the tower designer to distribute it in the most economical manner so that every part takes a full share of the heat-transfer process.

Mr. P. Betts: Are not Messrs. Kennedy and Margen exaggerating a little in suggesting that temperature ranges as low as 12°F were often used? As long ago as 1938 Lawton set an excellent example in choosing 17°F for Hams Hall A power station.* Lawton apparently proceeded by trial and error, but shortly afterwards Bottomley† showed how to arrive at the result directly, and in the post-war power stations where cooling towers have been more extensively used we are accustomed to cooling ranges of about 15–16°F at full load.

I am sorry to see that the authors regard Bottomley's method as unsuitable for turbines with high exhaust loadings. They say, "He assumed that the improvement in turbo-generator performance per degree Fahrenheit of water-temperature reduction was constant. . . ." This is not quite correct. Bottomley assumes that "exhaust area will if possible be increased with improved normal vacuum . . . in order to keep the percentage leaving losses constant," and he allows for the cost of doing this. Here it should be remarked that Table 1, being confined to twin exhausts, gives a false idea that exhaust loading inevitably increases with rating. In fact, with triple or quadruple exhausts and the somewhat longer blades now in prospect we would expect to be able to achieve a q_e of 1 100 even on 200 MW sets; this being so, Bottomley's assumption is not unreasonable. The fact that the largest possible exhaust is generally found economic is a further justification.

However, to take account of the case of a fixed exhaust size, giving a vacuum correction which is a function of temperature, we have for some time used the following modification of Bottomley's method. Consider, for simplicity, a river- or sea-cooled station. Assume a percentage rate of change of heat rate with vacuum temperature and assign a monetary value to it for energy (and power in peak-load season) and thus obtain a value of Z'_T, in Bottomley's notation. Then from his equations 4(a) and 4(b) the economic condenser surface S and water rate G for a given heat load W are obtained, and taking a given river or sea temperature with these values of W, S and G, a vacuum temperature may be calculated. By taking a series of assumed rates of change of heat rate, a curve relating percentage change of heat rate and vacuum temperature is obtained. Finally, a turbine vacuum correction curve can be plotted on the same graph, and its intersection determines the economic vacuum temperature. This method is admittedly not as detailed as the authors' in allowing for the averaging between different seasons, but it is much simpler and more rapid and perhaps as accurate as cost data would warrant.

I find eqn. (4) very obscure and cannot see the bearing of the relation between heat transfer resistance and friction power loss. Could this be explained in more detail?

Mr. D. Clark: My remarks are confined to Messrs. Kennedy and Margen's paper.

The frailty of generalized economic studies as a guide to practical decisions might with advantage have been emphasized, particularly as some of the assumptions that have been made about basic data to facilitate the calculations are debatable. In this subject there are pitfalls in arguing from the general to the particular. I hope the authors will agree that their findings should be regarded, not as rules for design, but as pointers to matters for study in connection with a new project.

For some time it has been realized that many past installations of cooling towers were over-liberally designed. In recent years economies have been effected, where possible, by installing more generating capacity without additional cooling towers or by omitting part of the originally projected cooling-tower installation when completing the development of the stations in question.

The opening sentence of Section 5 of the paper deserves to be heavily underlined. Except in the case of base-load stations, the practice of keeping all the available natural-draught towers in service at fractional loads can substantially improve the annual average recooled temperature and thermal efficiency. Failure to appreciate the merits of parallel operation has been the major fallacy in some past attempts to assess cooling-tower economics and may have contributed to over-liberal design. With mechanical-draught towers part-load operation must be a compromise, because of the high cost of keeping all the fans running.

In Section 4.3 the authors have evaded this issue in order to simplify the calculations, and presumably Fig. 7 is thereby biased against the natural-draught tower.

The mixed cooling system most widely used in current practice resembles Fig. 9(a) but with the recooled water returned directly to the inlet side of the condenser pumps. The arrangement which for many reasons is the most elegant is to return the recooled water to the river at a point mid-way between the station intake and the main discharge. No system is universally ideal; each station and situation must be considered on its merits.

With a mixed system, variable-speed drive of the separate cooling-tower pumps is unlikely to pay. Delicacy of control of such a system is ruled out by the sheer impossibility of providing operators with sufficiently accurate indications of the relevant conditions, in particular the river flow when the velocity is very low.

As regards Section 10.4.6, experience has shown that in a practical case many more than six periods have to be examined if any realistic conclusions are to be drawn. The study must include such combinations of extreme conditions as may be encountered over an extended period of years.

With regard to a policy for rivers, a good deal of work is in

* LAWTON, F. W.: "The Design and Operation of Hams Hall Power Station," *Journal I.E.E.*, 1939, 85, p. 469.

† BOTTOMLEY, W. T.: "The Economics of the Design of Condensing Plant and Cooling Water Systems as applied to Power Stations," *Transactions of the North-East Coast Institution of Engineers and Shipbuilders*, 1941, 57, p. 221.

hand in exploring the temperatures produced by power stations, not only in their immediate vicinity, but for some miles downstream. Similarly, both the British Electricity Authority and the River Boards are investigating the effects of temperature on fish and other life in rivers. Of necessity this is a long-term problem.

Those most closely concerned with these many-sided questions have long recognized that there cannot be any simple universal set of rules which will neither cripple the use of rivers for cooling purposes, nor, in some circumstances, be damaging to other interests. Temperature restrictions must have regard to the character and flow of the stretch of river in question and to the purposes for which it is or may in the future be used in the public interest. What may be acceptable in one place may be quite intolerable in others. Each power station proposal has to be considered on its merits in order to obtain consent under the Rivers (Prevention of Pollution) Act, 1951, and there is ample scope for the exercise of the British talent for compromise. Temperature conditions have now been agreed or determined in a sufficient number of cases to form a guide to the restrictions that may apply to any future site. Power-station designers are likely to have to rest content with progress on these lines.

Mr. C. G. Phillips: I am concerned with the design of special-purpose plant in some ways akin to power stations. Cooling is often involved, and the ratio of cooling power to installed power is not infrequently considerably higher than in power station practice; moreover, the cooling function is normally a more delicately involved component. All this infers that cooling towers have necessarily demanded my particular attention, and in this direction it early became noticeable that the temperature ranges normally regarded as good commercial practice were very much below what should be specified on overall economic grounds.

In a particular project, by raising the cooling-water temperature range from 15° to 30°F, the cooling-tower system cost was so much reduced as to bring the total plant cost down by 10%, despite the inevitable increase in primary cooler cost. Another, and larger, project included the requirement that temperature distribution across the large-area gas flow being cooled should be uniform to within ±2°F. All previous experience indicated that, if this were to be possible, the water-temperature rise must not exceed 10°F, but careful analysis led to a design which was able to halve the temperature distribution limits while doubling the temperature range on the coolant side. The cooler cost was little affected, but the cooling-tower cost was reduced by 30%.

I think it is often too readily assumed that a specific case demands water cooling. The assumption is probably valid where throw-away water is readily available, but in many other cases an appreciation of all the circumstances shows material advantages in favour of cooling by air. A practical case called for a particularly high thermal ratio, and water cooling was a foregone conclusion. As the plant developed, however, it became apparent that water cooling introduced a number of difficulties and disadvantages which air cooling would not. Pursuing this circumstance it was shown that air cooling need not necessarily be more expensive, everything considered, although to show to best advantage one was advised to avoid "normal" tube-and-fin construction and approach laminar flow. The particularly interesting point here is that the industry concerned was already aware that a special concern, in a water cooling system, would be the cost of coolers plus the cooling tower, as a result of which temperature ranges considerably higher than might have been expected were put forward. Otherwise there would have been no doubt at all that air cooling could enter competitively.

Finally, I realize that the authors were especially concerned with steam condensers. Even here, however, I see no reason why air cooling should be impracticable. My own brief examination of the possibility reveals nothing too disturbing, although it does perhaps suggest something rather unorthodox. The doubt which occurs to me is whether any other advantages would accrue, supposing one could show costs of the same order.

Mr. J. Leitersdorf: In Section 5 of the paper by Messrs. Kennedy and Margen reference is made to shutting down the fans under reduced load conditions. This is definitely the wrong procedure. The correct operation should make use of the enormous power saving which results from reducing the fan speed, whereby the air flow varies only directly as the fan speed while the power consumption drops as a cube function. This factor is important when considering the exhaust-heat load limitations which apply for any given steam turbine as described in the paper. Since for any particular case there will be no advantage in an increased vacuum when the wet-bulb temperature falls below the design value, advantage should be taken of the considerably reduced power consumption obtainable by reducing the air rate but at the same time maintaining the design water temperature.

In small cooling-tower installations the fan speed may be varied most readily by using 2-speed motors. In larger installations single-speed motors may be used in conjunction with an elementary form of frequency changer which will result in a simple, cheap and robust installation.

I should like to emphasize that 2-speed operation of the fans will produce all the necessary fluctuation one requires, and Fig. E

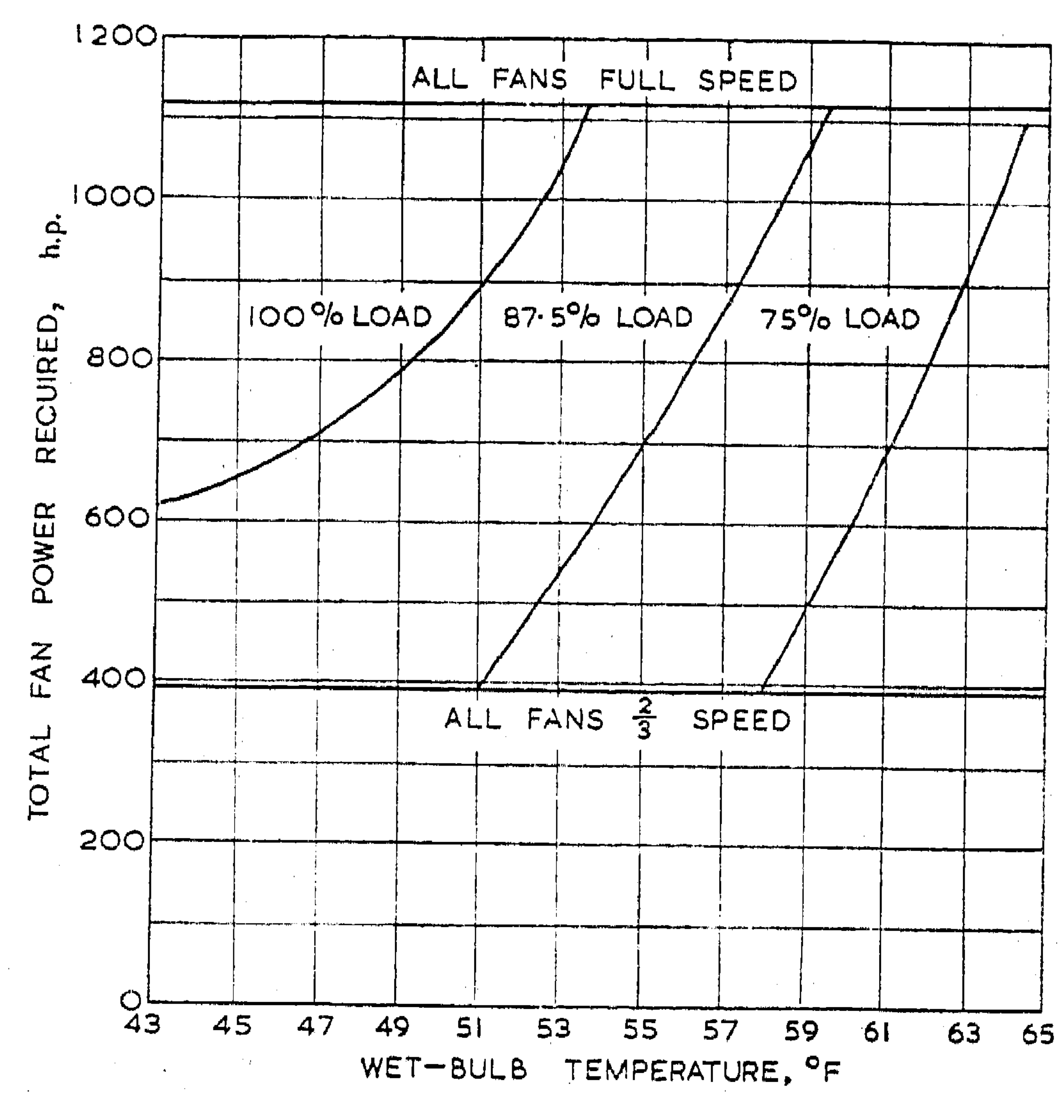

Fig. E.—Horse-power requirements of fans of induced-draught cooling towers for condenser of 110 MW turbo-alternator.

Vacuum	28·7 in Hg
Inlet-water temperature	83·8°F
Outlet-water temperature	65·8°F
Wet-bulb temperature	53·6°F
Water quantity	3 280 000 gal/h

has been drawn to illustrate this point. The curves are based on a scheme for a Continental power station utilizing automatic control to maintain constant vacuum by changing the fans from full-speed to part-speed operation according to requirements. It will be noticed that full-speed and two-thirds-speed fan operation has been used.

For the above reasons it is also completely misleading and incorrect to base economic calculations on seasonal block-load allocation diagrams (Fig. 2). Analysis in this manner must mean a much larger period of time calculated as full-load operation than occurs in practice. With horse-power varying as the cube of the fan speed the errors will be large; hence, accurate load

diagrams must be used in such an analysis which, unfortunately, will make the calculation tedious but very necessary to obtain accurate results. I believe that, if these necessary complete calculations are made, it will be found that the economic justification which mechanical-draught towers have achieved in all other parts of the world will be attained also in this country.

Finally, I should like to draw attention to an item which will also have a marked influence on economic comparisons made between mechanical- and natural-draught towers. Reference is made in Section 5 to the fact that economic water temperatures for mechanical-draught towers should be lower than those for natural-draught units. In Table 8 the difference is shown to be about 2°F, and this results in a cost figure in the economic comparison which is some three times larger than the net difference in cost in favour of natural-draught towers given in Section 10.3. Thus a difference of less than 1°F in one of these temperatures could completely alter the analysis in favour of a mechanical-draught tower. I believe that economic selections which rely on plant-capacity assessments as fine as this must necessarily be regarded with greatest care.

Mr. W. T. Bottomley (*communicated*): Messrs. Kennedy and Margen describe my paper as over-simplified referring to the constant vacuum correction in the typical example and not to the general mathematical theory. The paper was written in 1941, when the largest set on 29 in Hg normal vacuum at 3 000 r.p.m. had an economical rating of 24 MW. If the normal vacuum had been $28\frac{1}{2}$ in Hg for cooling-tower conditions, the exhaust area would have been smaller and the vacuum correction per degree Fahrenheit would not be appreciably affected by the change in the normal vacuum temperature.

The modern condition of large sets with a limited exhaust area can be dealt with by the general theory, and the solution obtained graphically using the vacuum-correction curve supplied by the turbine makers. The authors' Fig. 3 does not include the leaving loss due to the rotational kinetic energy of the steam.

The economic design, taking into account annual variations of the wet-bulb temperature and load, can be determined by the calculus of variations:

$$\text{Cost} = \int_0^1 f(S, W, A, v_s, v_c, P, t)d\tau$$

where τ is time in years.

This is a minimum when

$$dC = \int_0^1 \left(\frac{\partial f}{\partial S}dS + \frac{\partial f}{\partial W}dW + \ldots \text{etc.}\right)d\tau = 0$$

In Table 7 the efficiency could be improved at fractional station loads if more pumps were used and the maximum quantity of water pumped through the condenser with the head available at the pumps and using all the culverts. On the other hand, especially with river cooling and a tight exhaust, it pays to reduce the water passing through the condensers at full load in cold weather. Since these operating devices would be carried out whether the plant was economically designed or not, it is doubtful whether the investigation of the annual variations will materially affect the economical design as determined by the mean wet-bulb temperature.

I do not agree with eqns. (3), (5) and (9). Take eqn. (3*b*):

$$\frac{Q\partial t}{\partial Z} = \frac{Q\partial t}{z_A \partial A} = \frac{Q}{z_A}\frac{\partial t}{\partial h''_m}\frac{\partial h''_m}{\partial A}$$

$$= -\frac{C y_r H^{-1/3}}{1\cdot 5 z_A}\left(\frac{Q}{A}\right)^{5/3}\frac{\partial t}{\partial h''_m}$$

by eqn. (5*b*) in the paper by Mr. Margen, where $z_A = \dfrac{\partial Z}{\partial A}$

By comparison with eqn. (3*b*) in the paper, $z_A A^{5/3}$ is not the same as $Z^{5/3}$.

Eqn. (5) should read

$$\frac{Q\partial t}{\partial Z_s} = \frac{Q\partial t}{z'_s \partial S} = \frac{Q}{z'_s}\frac{\partial t}{\partial (Q/KS)}\frac{\partial (Q/KS)}{\partial S} = -\frac{1}{z'_s K}\left(\frac{Q}{S}\right)^2\frac{\partial t}{\partial (Q/KS)}$$

where $z'_s = z_s + z_P\left(\dfrac{\partial P}{\partial S}\right)_{v_s}$

K is constant because it is a function of the velocity, which is an independent variable.

The partial differential in eqn. (7) should be based on the assumption that the surface and velocity are constant, being independent variables and therefore based on constant logarithmic mean temperature difference. The right-hand side of eqn. (7) should be $0\cdot 19$ for the conditions shown in Table 7.

Eqn. (9) should read

$$\frac{Q\partial t}{\partial Z_w} = \frac{Q\partial t}{z'_w \partial W} = \frac{Q}{z'_w}\frac{\partial t}{\partial(\Delta\theta)}\frac{\partial(\Delta\theta)}{\partial W}$$

$$= -\frac{1}{z'_w}\left(\frac{Q}{W}\right)^2\left[0\cdot 19 + \frac{\partial(\theta_m - t_{w1})}{\partial(\Delta\theta)}\right]$$

where $z'_w = z_w + z_P\left(\dfrac{\partial P}{\partial W}\right)_{v_c}$ and z_w is the extra cost of the culverts per pound per second of extra water at constant velocity, the velocity being an independent variable.

In the paper by Mr. Margen the economic design of cooling towers is uniquely based on the assumption in eqn. (2) that the heat transfer rate is directly proportional to the air mass-flow rate. This assumption is clearly incorrect. Data are available on the transfer rate of air flowing outside and at right angles to a number of staggered rows of tubes which show that the transfer rate is proportional to the $0\cdot 6$th power of the air mass-flow rate,* and the condition in the tower should be similar. G cannot be eliminated in eqn. (5) in the manner shown.

Mr. W. F. Carey (*communicated*): Mr. G. J. Williamson's suggestion that, for a given pressure drop, grids would offer three times as much transfer as splash-bar packings would lead to natural-draught towers of the type shown in Fig. F; the apparent radical departures from present practice are all in more or less common use in absorption towers in the chemical industry. When executing the cooling duty between the streams of air and water in Fig. G, an 8 ft depth of grids will afford a maximum gas flow; for a tower 350 ft high the mean air speed through the grids will be about 5 ft/sec, being determined by the balance of the propulsive and the resistance heads somewhat as shown in Table B.

Table B

Propulsive heads	Air head	Resistance heads	Air head
	ft		ft
330 ft of air 10°C above ambient air temperature	11	Eliminator $3 \times 5^2/64\cdot 4$	$3\cdot 5$
		Packing $8 \times 3\cdot 2 \times 5^2/64\cdot 4$	$10\cdot 0$
20 m.p.h. cross-wind	6	Inlet and exit loss $2 \times 10^2/64\cdot 4$	$3\cdot 1$
Total:	17		$16\cdot 6$

* McAdams, W. H.: "Heat Transmission" (McGraw-Hill, New York, 1942) second edition, p. 229.

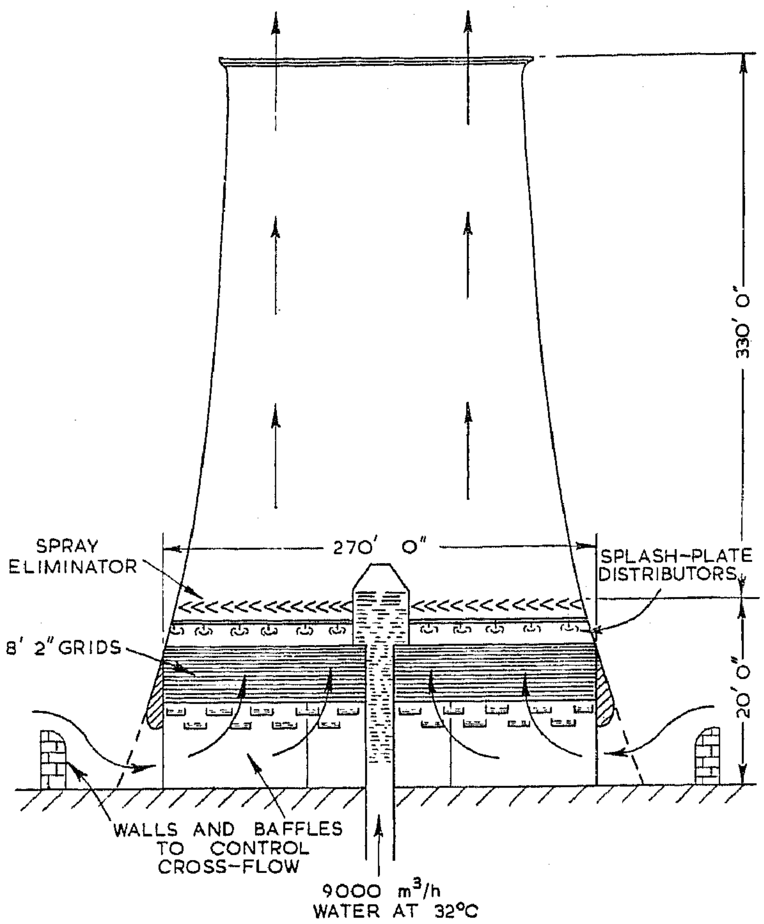

Fig. F.—Grid-packed natural-draught cooling tower.

The water rate through the tower will be $0 \cdot 2\,m^3/h\text{-}ft^2$ (cross-section) and will wet only 35% of the surface of ordinary 2in × 2in grids; by using grids in which there is a shallow horizontal groove, complete wetting can be obtained.

The cost of producing $9\,000\,m^3/h$ of cooling water in such a tower will then be as follows:

	d./m³
Cost of tower and packing	0·25
Cost of 5% make-up at 3d./m³	0·15
Pumping and miscellaneous	0·10
Total	0·5

The problem of finding the most economical temperatures of a river-water condensing system is a question of considering the minimum sum of the costs of surface and of water plus the value of the steam energy lost by not achieving a vacuum corresponding to the temperature of the cold water. A solution sufficiently close for preliminary design can be obtained by substituting the following technical and economic factors in the formulae given by Carey and Waring.*

Symbols used by Carey and Waring	*Significance*	*Typical numerical values*
C_w	Cost of cooling water	0·5d./m³
C_s	Cost of 1 steam kilowatt-hour	0·4d./ft²/annum
a	Annual cost of condenser surface including water friction	90d./ft²/annum
H_0	Overall transfer coefficient in condenser tubes	$150\ \dfrac{\text{kcal}}{\text{ft}^2\text{-h-}^\circ\text{C}}$
m	Operating time	5 000h/annum

The results of this calculation show that the mathematical minimum cost obtains for a water-temperature rise of 20·5°C and an approach of 1·9°C to the steam temperature. The transfer diagram (Fig. G) has been prepared much on the lines suggested by Messrs. Kennedy and Margen; the exchange in the steam condenser incorporates slight adjustments to the strictly economic temperatures, thereby reducing the capital charges without greatly increasing the total operating cost. The diagram also includes the cooling-tower exchange by the artifice of using temperatures of saturated air with the same total heat. By comparing the annual charges of transferring 1 kcal/h-degC in the tower and in the condenser, it is found that transfer in the tower costs only half that in the condenser; consequently it will pay to cool the water to 3° C (or less) above the wet-bulb temperature. It would be expensive to achieve such a loose approach with conventional tower designs, owing to the cross-flow of the air at the entry to the packing.

* Carey, W. F., and Waring, A. H.: *Transactions of the Institution of Chemical Engineers*, 1934, 12, p. 158.

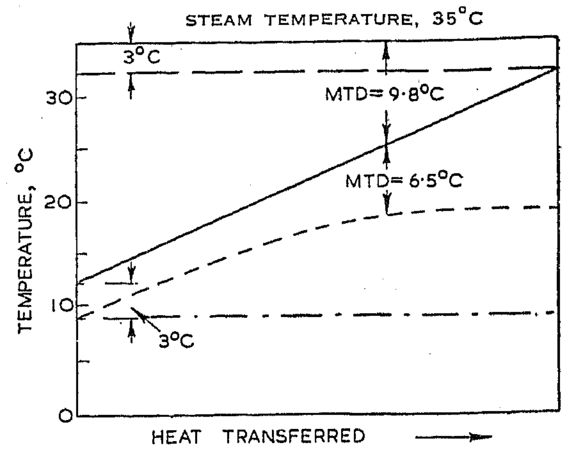

Fig. G.—Heat-transfer diagram for condenser cooling-tower system.

——— Water temperature, 12°–32° C.
— — — — Equivalent air temperature, 9°–19° C.
—·—·—·— Wet-bulb temperature, 9° C.

The equivalent air temperature is that of saturated air which has the same total heat as the tower air.

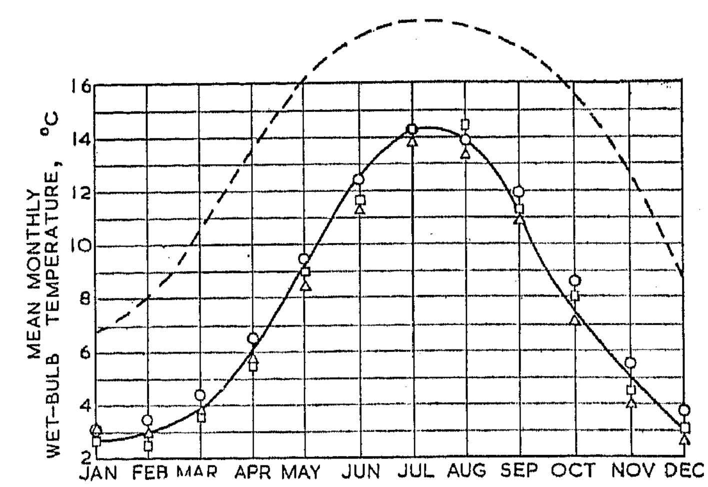

Fig. H.—Mean monthly wet-bulb temperatures.

— — — — Industrial river temperatures.
——— Wet-bulb temperatures (measured in Stevenson screen).
○ ○ Kew (1871–1915).
△ △ Sealand (1922–34).
□ □ Cranwell (1921–34).

Fig. H shows the seasonal changes in the wet-bulb temperature from 3°C in the winter to 14·5°C in the summer and the corresponding temperature for some industrialized rivers. Whether cooling is derived from towers or rivers these changes will affect the sink temperature but not the economic differences. Thus, with cooling towers the turbine vacuum will swing from 27·7in in the summer to 28·8in in the winter. This may result in appreciable carry-over loss in the cold weather, but would be offset by the extra energy recovered during the summer months.

Thus there might be quite a number of situations in which power stations could use cooling towers with little if any greater cost than river water. However, this depends upon achieving counter-current exchange in cooling towers with very low wetting rates; full-scale experience will be necessary before this possibility can be applied commercially with confidence.

MERSEY AND NORTH WALES CENTRE AT LIVERPOOL, 10TH JANUARY, 1955

Mr. W. H. C. Pilling: The paper by Messrs. Kennedy and Margen emphasizes the importance of co-ordinating the design of the condensing plant, circulating-water plant and cooling towers to ensure that the overall cooling system is economic in capital and operating costs.

The authors have shown that quite large economies are possible by proper attention to these aspects, but I feel that we must be careful not to go too far because there are certain practical factors to be taken into account. I have in mind particularly the icing conditions which occur in cooling towers in spite of the various de-icing devices which are usually incorporated. Under such conditions the effective capacity of the tower is reduced and some margin on design is necessary to avoid reduction of station output or loss of efficiency.

Table 4 compares the original design of the cooling-tower scheme and the new design, but I should like more information on the saving shown in circulating-water pumping costs, which seems to be higher than I would have thought possible. I should also like some information on the £7 000 saving on piping, culverts, valves, etc.

Whilst I agree with the authors in Section 4.1, I think we are in some difficulty at the present time in that we are dependent on the makers' designs for the dimensions of the l.p. end.

Mr. H. Bateman: The circulating-water requirement of a modern generating station is one of the major factors to be considered in the selection of a new station site. The authors mention that few rivers in this country are large enough for direct-cooled systems and illustrate a case for combined river and cooling-tower schemes in Section 6 of the paper. This case is founded by making the best use of the difference in river flow caused by seasonal change.

There is, however, another type of site located on the tidal reaches of a medium or small river where there is, in addition to seasonal variation in river flow, a considerable variation in the tidal flow past the site. In this case, during dry weather or even under average conditions there may only be sufficient water flowing for, say, 6–8 hours of each tidal cycle to meet direct cooling requirements.

Do the authors generally consider the adoption of a combined river and cooling-tower scheme under these conditions to show economic merit over a straight cooling-tower scheme in which fresh water make-up is extracted from the river between tides? If so, would they please comment on the type of tower and the practicability of operating such a combined scheme?

Although the introduction of eliminators in towers effects a considerable reduction in carry-over losses, there is still an appreciable loss of water from a cooling-tower system resulting in continuous make-up and purge requirements. Would it not be economic and practicable to consider means of further reducing this loss, e.g. by electrostatic precipitation?

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Messrs. G. F. Kennedy and **P. H. Margen** (*in reply to the discussion on the first paper*):

Method of Cooling Tower Selection.—Papers describing economic studies are usually faced by one of the following two criticisms:

(*a*) The calculations are not worth while, because total-cost curves are sensibly flat near the minimum point so that a moderate error in design produces no significant cost increase.

(*b*) Generalized economic solutions cannot be applied to practical cases, because local conditions vary greatly.

Having avoided comment (*a*) by showing that very large savings are possible compared with past tower selection practice, which definitely did not locate the cooling towers on the sensibly flat range of the total-cost curve, we have met some comment of type (*b*).

Variations in local conditions have, however, less effect than one might suppose. For instance, as pointed out by Mr. Brown, a 15-hour average atmospheric wet-bulb temperature should be used for 2-shift stations, and a 24-hour average for 3-shift stations. The average difference, however (which amounts to $1 \cdot 5^\circ$ F), would increase the total annual cooling tower cost, Z, by less than $0 \cdot 2\%$ if the wrong average were chosen. In a similar way, most other variations in local conditions ignored by our charts do not remove the towers from the flat range of the total-cost curves, and more detailed estimates are worth while only where the special data, skill and time are readily available. As the cooling tower is the last major non-standardized plant item in British power stations, charts which speed up the tower selection process at least for straight-cooling-tower stations will tend to reduce the present excessive generating-station planning time.

Trend of Tower Selection.—Our conclusions concerning the trend of cooling tower selection have been accepted by nearly all speakers, particularly the fact that towers and water quantities were too large in the past and that the trend towards relatively still smaller units will continue as turbine exhaust-heat ratings increase. What has been challenged, by some speakers, is our statement that turbine exhaust-heat loadings will continue to increase as turbine ratings grow. The reasons for our statement are obvious, but their effect might be at least partially counteracted by the development of superior steels which will permit the use of higher blade velocities or greater blade lengths. The economic design of the turbine exhaust is of great importance, and we hope that turbine designers will devote a paper to this subject to complement the studies now available for cooling towers and condensers.

Utilization of Rivers.—We are encouraged by Messrs. Brown and Clark's statements that the B.E.A. and River Boards are studying the permissible degree of heat rejection to rivers, and by their personal views that large quantities could be rejected with great benefit to industry without undue interference with other interests. We agree that such investigations must be conducted for each river, but plead for the instantaneous publication of the results of each inquiry in order to guide future planning. One cannot feel completely reassured about the present position when several straight-cooling-tower stations are being constructed on sites admirably suited technically for combined river and cooling-tower schemes.

In reply to Mr. Carey, the economic difference between the vacuum temperature and the sink temperature is about 14° F more for British cooling-tower stations than for river stations, as shown by the information in Table 3 and Fig. 4(*a*). Hence river stations preserve their vacuum advantage even for slightly higher sink temperatures.

Mr. Donkin's remarks show that straight-cooling-tower schemes tend to be more favourable in certain tropical countries than in Britain.

Cooling Tower Operation.—Messrs. Clark and Bottomley endorsed our view that natural-draught towers should be kept permanently on load and that the water quantity should be reduced to relatively low values on cold days and at times of low station load. These points cannot be impressed too strongly on the operating staff.

Mr. Leitersdorf has pleaded for the use of 2-speed or variable speed motors. We have examined such proposals from time to time, but found, for each power station application, that the extra cost of the more complicated motor at least cancelled out the advantage due to the reduction in auxiliary power. Progress in developing cheaper and more convenient methods of speed control may alter this position, and we welcome Mr. Leitersdorf's investigations. One must, however, remember that vacuum temperature control, by reducing the circulating water quantity on cold days, achieves economies in auxiliary power even with constant-speed fan drives and limits the extent to which further economies can be realized by fan speed regulation.

Method of Calculation.—In reply to Mr. Brown, the figures in Table 4 fully allow for the change in the heat transfer coefficient which affects the logarithmic mean condenser temperature difference but not, in general, the terminal temperature difference.

Though we have criticized one assumption made by Bottomley, we wish to pay tribute to the clarity of his 1941 treatise on economic circulating-water system design.[1] The assumption we criticize, and which appears to be partially defended by Mr. Betts, is that the capital cost increment required to maintain the leaving loss constant for 1° F reduction in vacuum temperature is constant. This assumption can lead to large errors with the high turbine exhaust loadings now in use; for example, it can produce the incorrect conclusion that the economic sizes of cooling towers, condensers and circulating-water pumps can be determined independently of one another.

The statement concerning our eqn. (4), queried by Mr. Betts, is explained by

$$p_c \propto V^{2\cdot 8},\ r_c \propto V^{-0\cdot 7}$$

so that

$$p_c \propto r_c^{-1/4}$$

where p_c = condenser friction power, r_c = heat transfer resistance, and V = water velocity.

Mr. Bottomley criticizes our eqns. (3*b*) and (5), but himself derives equations which become identical with these when they are rewritten in terms of our symbols. His disagreement with eqn. (9) is due to the fact that he has assumed constant water velocity and variable tube length in determining the economic water quantity, whereas we have assumed variable water velocity and constant tube length. Either method is legitimate and both give the same final result for the economic water quantity.

Miscellaneous.—Mr. Carey has proposed a natural-draught tower with film packing, in which the packing surface, cooling range and approach to the wet-bulb temperature are respectively about 1·3, 2·0 and 0·5 times the values we have recommended in the two papers. The main reason for Mr. Carey's different conclusions is that he has used water make-up costs far higher than those customary at power stations and has taken them to be proportional to the circulating water quantity, thus placing a premium on low water quantity. With towers containing eliminators, make-up costs are proportional to the evaporation and should not therefore be allowed to influence the tower design.

Mr. Philipps's proposal of an air condenser (made also by Mr. J. F. Field in discussing Wood and Betts's paper), imposes great difficulties in leading air ducts through the station.

Despite Mr. Pilling's remarks, we believe that the icing problem calls for the improvement of de-icing devices, and not for larger towers, just as the answer to the carry-over problem was provided by good louvre eliminators and not by larger towers as previously thought. The residual carry-over loss now estimated at about 0·01% of the circulation leaves no economic margin for the more expensive electrostatic eliminators suggested by Mr. Bateman.

For the tidal river site mentioned by Mr. Bateman, it would seem worth while comparing the economics of (i) pure river cooling plus large-scale water storage, (ii) river plus tower cooling, and (iii) straight tower cooling, considering both natural and mechanical draught towers for (ii).

Mr. P. H. Margen (*in reply to the discussion on the second paper*):

I am especially indebted to Mr. Williamson for contributing Figs. A and B and to Mr. Lowe for contributing test results on three corrugated sheet packings, which have been added as points *g*, *h* and *i* to Fig. A. All the film packing results lie reasonably close to the general correlation, though they do not, of course, remove the need for further experimental work stressed by Messrs. Chilton and Lowe.

In dealing with splash-bar-packing test results such as those on Mr. Williamson's Fig. B, I recommend that the heat transfer and friction numbers be expressed per unit packing plus pumping cost instead of per unit surface, in order to allow for the effect of the widely varying pumping costs with different packings and load factors. Thus one may write

$$C = (F + f's')^{1/3}(1/k's' + 1/2) \quad . \quad . \quad . \quad (A)$$

where $f' = f/x,\ k' = k/x,\ s' = sx \quad . \quad . \quad . \quad . \quad (B)$

and x = (packing cost + pumping cost)/(reference packing cost)

$$= (z_s + z_w w/a\eta_w)/z_{s0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (C)$$

The reference cost, z_{s0}, may conveniently be taken as the value of z_s for 2 in × 2 in × $\frac{3}{8}$ in serrated grid packings.

Fig. I shows a heat-transfer/friction correlation drawn on this new basis by plotting k' versus f' for Messrs. Lowe's and

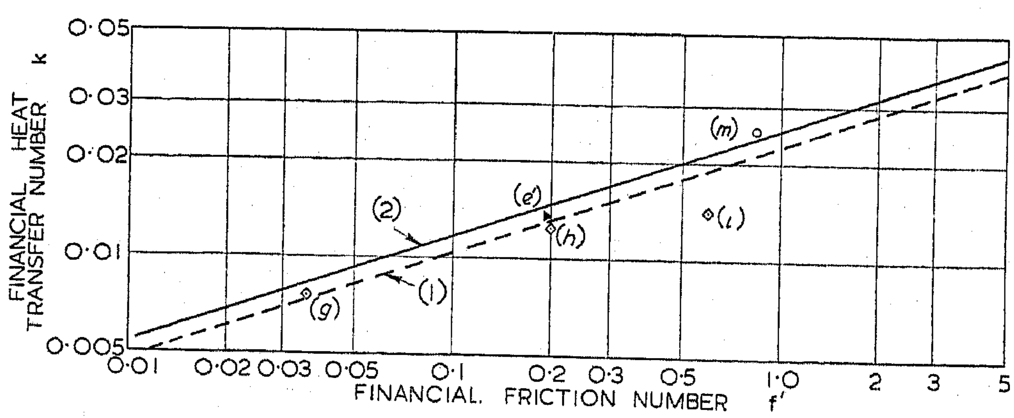

Fig. I.—Friction-heat transfer correlation on cost basis.

Cost constants as for Table C.

(*g*), (*h*), (*i*) Corrugated-sheet packings, data by Lowe [$a = 15\,ft^{-1}$ for (*g*) and (*h*) and $7\cdot 5\,ft^{-1}$ for (*i*)].
(*e'*) Grid packing, Mr. Williamson's Fig. B ($a = 13\,ft^{-1}$).
(*m*) Splash-bar packing, Mr. Williamson's Fig. B (a assumed to be $1\cdot 3\,ft^{-1}$).

Curve (1) Original k/f correlation for film packings assuming $a = 13\,ft^{-1}$.
Curve (2) Proposed new k'/f' correlation, $250k' = (250f')^{1/3}$.

Williamson's test data. The Figure also contains curve 1 giving the same k and f values as the original "general correlation," and curve 2 having the now more convenient equation

$$250k' = (250f')^{1/3} \quad . \quad . \quad . \quad . \quad (D)$$

For packings satisfying this correlation, the design chart and equations in the paper apply directly if k', f' and s' are used instead of k, f and s.

The most interesting point in the Figure is that the splash-bar packing lies above the full line, i.e. gives a figure of merit

$$R' = 250k'/(250f')^{1/3} \quad . \quad . \quad . \quad . \quad (E)$$

of 1·05 compared to the value 0·93 for the grid packing. Consequently the splash-bar packing is the more economical one to use, particularly for high-friction and low-load-factor applications. It is worth noting that for packings with the optimum friction and surface, the total packing plus pumping cost per unit A for a given performance coefficient varies as $(1/R')^{3/2}$. Hence Mr. Williamson's splash-bar packing has a 17% packing plus pumping cost advantage over his film-type packings for medium-friction applications. This is also illustrated by a worked example in Table C, Part IV.

Mr. Chilton's Table A provides a striking illustration of the small effect on costs of even substantial departures of certain design variables from their calculated optimum values. He has, however, used a constant shell friction throughout, whereas this can vary over a range of 10 to 30 velocity heads. Hence more substantial savings than he suggests are obtainable in extreme cases by developing more than one type of standard packing.

The preceding analysis of Mr. Williamson's test results suggests that this state of affairs already exists to the extent that the splash-bar packing must be regarded as a good high-friction design and the grid packing as a fairly low-friction design.

I hope Mr. Carey will publish test results for the interesting grid packing with horizontal grooves he has mentioned.

Mr. Bottomley's criticism amounts to a disagreement with the approximation, $C \simeq$ (constant) for varying w and G, which has in fact been a subject of controversy since it was first proposed by Chilton.[3] In my view, Chilton's test results justify the use of this approximation for the particular problems I have dealt with, whereas it was necessary to apply a correction in determining the economic water quantity in the other paper. The approximation does not necessarily imply $k \simeq$ (constant), since the effect of changes in k is partly offset by that of associated changes in f.

Table C

PERFORMANCE OF WILLIAMSON'S FILM AND SPLASH-BAR PACKINGS

(At reference conditions, $w = G = 0\cdot36$ lb/sec-ft², $L_w = 0\cdot5$)

Symbol	Description	A	B	B/A
		Film packing	Splash-bar packing	
	I *Surface Basis*			
k	Heat-transfer number	0·016	0·071	4·4
f	Friction number	0·23	2·4	10·4
R	Figure of merit (eqn. 19)	1·04	2·11	2·04
	II *Volume Basis*			
a	Surface per ft³ ft^{-1}	13	(1·3)*	0·1
ka	1/(height of transfer unit) ft^{-1}	0·21	0·092	0·44
fa	1/(height of friction unit) ft^{-1}	3·0	3·1	1·03
	III *Cost Basis*† [eqns. (B) and (C)]			
k'	Financial heat-transfer number	0·0135	0·0249	1·84
f'	Financial friction number	0·194	0·842	4·34
R'	Financial figure of merit	0·93	1·05	1·13
$(1/R')^{3/2}$	Packing + pumping cost index	1·12	0·93	0·83
	IV *Design Examples*			
F	Shell resistance	20	20	1·0
s	Packing surface per unit A	70	24·2	—
s/a	Packing height, ft	5·4	18·6	—
s'	Total relative packing* + pumping cost [eqn. (B)]	83	69	0·83
C	Performance coefficient [(eqn. (6) or (A)]	4·6	4·6	1·0

* Typical value is used, since actual value is not known.
† Assuming $z_s/z_{s0} = 1\cdot0$, $z_w w/\eta_w z_{s0} = 2\cdot4$ ft^{-1} at reference conditions.

DISCUSSION ON "ALTERNATING-CURRENT-INSTRUMENT TESTING EQUIPMENT"*

BEFORE THE NORTH-EASTERN RADIO AND MEASUREMENTS GROUP, AT NEWCASTLE UPON TYNE, 15TH NOVEMBER, 1954

Mr. E. D. Taylor: When testing instruments to 0·1% accuracy, what arrangements does the author make regarding heat stability of the instruments under test? Are spot readings taken, or are the current and voltage maintained at each reading until the instruments have attained a steady-temperature state?

I cannot agree with the author that rectifier-type instruments can ever be used as substandards. They are very susceptible to changes of temperature, ageing and frequency, and the lowest permissible error given in B.S. 89: 1954 is 2·0%. An instrument that has been calibrated can, for a limited time, be used as a rough standard for calibrating other rectifier instruments.

Apart from rectifier-type instruments, the indications of most other types of a.c. instrument are independent of reasonable waveform departure from a sine wave. Therefore there does not seem to be much object in striving for such low harmonic contents in the test waveforms, especially since, in practice, waveforms are often far from pure.

Finally, with the great strides in the development of magnetic materials, is it possible that what is termed the "moving-iron" instrument will become a reliable precision transfer-type instrument?

Mr. B. Berger: The problem often arises that one wishes to make an accurate measurement of an alternating quantity having

* ARNOLD, A. H. M.: Paper No. 1532 M, April, 1954 (see 101, Part II, p. 121).

a small harmonic content. A knowledge of the relationship between instrument error and harmonic content would greatly help in deciding (*a*) which type of movement would be most suitable, and (*b*) which accuracy grade should be selected. A precision instrument is calibrated under ideal conditions and is then often used under adverse circumstances (e.g. instability of supply, harmonic content). This is permissible provided that these adverse circumstances can be expressed as an equivalent instrument error. It would be interesting to know whether the author has carried out an investigation to determine the errors of commercial precision instruments due to waveform distortion.

The use of an indirectly heated thermistor as an a.c./d.c. transfer device was described in a recent paper.* Does the author think that these elements offer any advantages over vacuum-junction thermocouples, especially regarding their sensitivity and reversal error?

Mr. H. M. S. Smith: A brief reference is given in the paper to the use of junction thermocouples as transfer standards. Another recent paper has referred to some of the errors found in such couples, such as, for example, $0 \cdot 1\%$ frequency error and $0 \cdot 1\%$ error due to temperature gradient along the heater. One wonders whether a sufficiently accurate estimation of these errors can be made and whether the errors will be stable with time. If proved to be satisfactory in these respects, such instruments obviously become attractive. Perhaps the author would also say whether thermistor elements can be used, and whether the hot-wire comparator technique has been reconsidered for high-frequency transfer measurements.

The author briefly described a screened voltage divider of a type similar to one I have recently constructed. In my case, however, the auxiliary divider was a capacitor-divider, thus economizing in space. For complete compensation, an infinite series of auxiliary dividers is theoretically necessary, and this is obviously impossible. I should like the author's views on the maximum voltage up to which a single auxiliary divider would be practicable, particularly bearing in mind the phase error of the divider.

Mr. G. White: The author states that he prefers to maintain the temperature of the standard Weston cell at a constant value rather than to correct for temperature change, since some cells exhibit a hysteresis effect with temperature changes, which may give rise to errors. Would he tell us the magnitude of these errors?

How often are the standard instruments at the N.P.L. checked?

Although the vacuum junction standard is very good as a transfer instrument, how does it compare with the electrostatic and dynamometer instruments with regard to stability?

The author points out that the more recent transfer resistance standards at the N.P.L. have been built with nickel-chromium-aluminium conductors, since this alloy has a negligible temperature coefficient of resistance. How does it compare with manganin or copper nickel?

Mr. G. E. Moore also contributed to the above discussion.

Dr. A. H. M. Arnold (*in reply*): It would be a wasted effort to attempt to calibrate an instrument to $0 \cdot 1\%$ accuracy if its error were dependent to a large extent on temperature, frequency, waveform and other factors. Instruments complying with the precision grade of B.S. 89 are usually tested as soon as possible after the application of voltage or current. Industrial grade instruments are tested after being in circuit for 30 min in accordance with the provisions of B.S. 89. I agree with Mr. Taylor that rectifier-type instruments are not satisfactory standards: if they are used for calibrating other rectifier instruments they should be checked at frequent intervals.

Moving-iron instruments have been greatly improved by use of high-permeability alloys, but I would prefer not to use one as a transfer instrument.

The principal justification for testing with a sinusoidal waveform is that it is a standard condition of testing so that the consistency of behaviour of instruments can be checked. If it is suspected that an instrument has large waveform errors it is desirable to make an additional test on a bad waveform to check this point. It is, however, seldom possible to calibrate an instrument for normal conditions of use since these are not generally known. It would be a very expensive matter to determine the effect of each harmonic, including the effect of phase, and Mr. Berger would do better to choose an instrument free of waveform errors rather than to attempt to calibrate one with large errors. His reference to the use of a thermistor as an a.c./d.c. transfer instrument is interesting. The accuracy claimed in the paper he refers to is only $0 \cdot 2\%$, but it is quite likely that better results than this can be obtained. I do not know whether the best type of thermistor would prove superior to the best type of thermocouple. There is, of course, a danger in thinking of either a thermistor or thermocouple as inherently suitable for a particular duty, and Mr. Smith points out some of the errors which are sometimes found in thermocouples. The best basis for a satisfactory a.c./d.c. transfer is to use a number of independent methods. The higher the frequency becomes, of course, the more difficult this is to do.

There are too many variables involved to give a direct answer to Mr. Smith's question about voltage dividers. A better approach, with a particular problem to be solved, would be to consider which method of voltage division would yield the most economical design for the accuracy required. Mr. White's question with regard to standard cells raises a number of important points. A true hysteresis effect in a standard cell is an undesirable feature which fortunately is not very common. In some cases we have observed a temporary change of e.m.f. of up to $100\,\mu V$ after a temperature cycle of $10^\circ C$. In addition to this, however, if a standard cell is allowed to change temperature rapidly there is a danger of inequality of temperature between the two limbs which may cause a serious change of e.m.f., and there is a danger of the standard cell temperature differing from the temperature recorded by the thermometer.

The standard deflecting instruments used at the N.P.L. are calibrated every day and sometimes more than once in a day. Transformers, resistors and standard cells are calibrated at intervals ranging from three months to more than a year according to circumstances. The thermocouple vacuum junction has inferior stability to electrostatic and dynamometer instruments, and the d.c. and a.c. measurements should not be made at times differing by more than a few seconds. It is generally desirable to repeat both measurements several times.

The temperature coefficient of nickel–chromium–aluminium–copper wire may be made zero at a chosen temperature and this may also be achieved for manganin and copper–nickel. When this has been done, and it is much easier with the first-named alloy than with the other two, the rate of change of temperature coefficient with temperature of nickel–chromium–aluminium–copper may be about one-tenth that of manganin and one-half that of copper-nickel.

* BOCKRIS, J. O'M., and BOWLER-REED, J.: "The Measurement of Dielectric Constants of Conducting Liquids," *British Journal of Applied Physics*, 1951, 2, p. 74

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PROBLEMS OF HYDRO-ELECTRIC DESIGN IN MIXED THERMAL–HYDRO-ELECTRIC SYSTEMS

By T. G. N. HALDANE, M.A., M.I.C.E., Past-President, and P. L. BLACKSTONE, T.D., M.A., Member.

(*The paper was first received* 21*st May, and in revised form* 3*rd August*, 1954. *It was published in November*, 1954, *and was read before a Joint Meeting of* THE INSTITUTION *and* THE INSTITUTION OF CIVIL ENGINEERS 6*th January, the* NORTH-WESTERN SUPPLY GROUP 8*th February, and the* SOUTH-EAST SCOTLAND SUB-CENTRE 19*th April*, 1955.)

SUMMARY

The paper deals with some of the problems which arise in the planning and development of a system comprising both thermal and hydro-electric plant. In general, when thermal plant predominates it is considered desirable to develop hydro-electric power with the greatest installed capacity the system can absorb in conjunction with the available amount of energy. Practical limitations to low-load-factor operation are discussed.

The effects of the introduction of low-load-factor hydro-electric plant on system operation and on the overall fuel consumption of the thermal plants are examined. New circumstances which cannot readily be forecast may later make desirable a change in the design load factor of some of the hydro-electric plants, and the paper stresses the advantage of having, where possible, flexibility in the initial design to enable such changes to be made. Where circumstances permit, consideration of the use of pumps, and especially reversible pump-turbines, is recommended as a means of augmenting storage capacity and either increasing the firm annual load factor or permitting increased installed capacity.

The basic economics of the pumped-storage scheme are explained and an example illustrating the flexibility which is possible in planning such an installation is given in the Appendix.

The paper discusses the effect on hydro-electric development of the possible ultimate replacement of coal and oil by nuclear fuel in thermal plants, and it is concluded that hydro-electric plant is likely to continue to be advantageous for peak-load operation and that there is no justification for any postponement of long-term investment in hydro-electric works on account of the advent of nuclear power.

The effect of rising prices is also discussed, and a general survey is given of present practice in the design of hydro-electric machines. Transmission practice and problems are briefly reviewed as an integral part of hydro-electric design.

In conclusion it is pointed out that differences of opinion between thermal and hydro-electric engineers may arise because of inadequate mutual understanding of the inherent characteristics of the two types of plant and of the problems of combined operation. The design of hydro-electric projects in a mixed system must be based, not only on the hydrographical and civil engineering data, but on a comprehensive study of all the many factors involved.

(1) INTRODUCTION

During the last quarter of a century the development of hydro-electric resources has increased approximately fourfold, the total world installed capacity of hydro-electric plant being now about 90 million kW. This rapid development is in part due to technological advances, particularly in high-voltage transmission, which have made it possible to harness on an increasing scale hitherto unused resources, some of which are very distant from the load supplied. In part, also, the rapid development is due to rising costs of fuel and shortages of indigenous fuel in certain countries. Although a threatened shortage of indigenous fuel may greatly affect the national power policy, the cost of thermal generation is the main criterion in deciding whether any hydro-electric project is, or is not, worth constructing.

Thermal and hydro-electric plant are to a considerable extent complementary, and advantage is usually obtained from a mixed system. This mixture of plant has created certain interesting design problems which are examined later. Table 1 shows the proportions of thermal and hydro-electric plant in various countries of the world, and it will be noted that this proportion varies over a wide range.

Table 1

APPROXIMATE PROPORTIONS OF THERMAL AND HYDRO-ELECTRIC PLANT IN VARIOUS COUNTRIES*

	Thermal %	Hydro-electric %
England and Wales	99·7	0·3
Australia	88·1	11·9
Germany (Western)	81·1	18·9
United States	77·8	22·2
Scotland	69.4	30.6
France	55·5	44·5
Finland	39·8	60·2
Japan	37·4	62·6
Sweden	22·7	77·3
Italy	18·3	81·7
New Zealand	11·5	88·5
Canada	9·6	90·4
Switzerland	6·6	93·4
Norway	4·2	95·8

* Source: *United Nations Bulletin of Statistics*, November, 1953.

In examinations of the combined use of thermal and hydro-electric plant in large integrated systems there are two concepts which are commonly used. The first is the annual load/duration curve with the various types of plant fitted into the area embraced by the curve; an idealized diagram of this type is shown in Fig. 1. Although such diagrams can be of help, they have considerable limitations and unless used with caution may lead to erroneous conclusions. Before decisions about a hydro-electric project are reached it will be necessary to make more detailed studies on a daily or short-period basis, and a method of doing this is described in Section 2.2.

The second concept is that of the annual load-factor of hydro-electric stations, although this is somewhat ambiguous and should also be used with caution. The firm annual load-factor of a hydro-electric project can be defined as the ratio of the energy output which can be relied on in any year (including very dry years) to that which would be generated if the installed plant

This is an "integrating" paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Haldane and Mr. Blackstone are with Merz and McLellan.

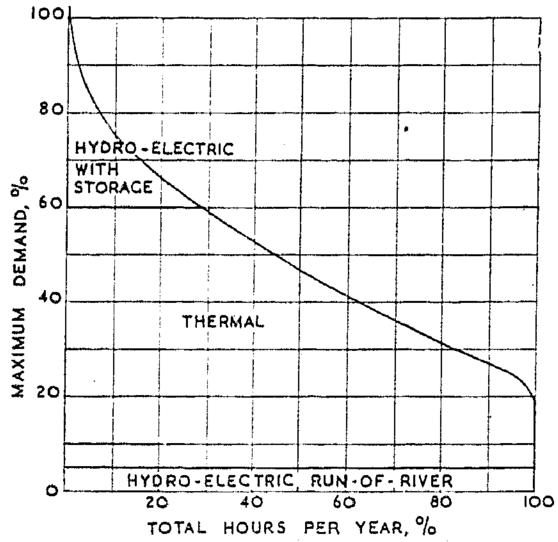

Fig. 1.—Idealized load/duration curve.

operated at full load throughout the year. The average annual load-factor of a hydro-electric project is the similar ratio for the average output over a long period of years, and therefore includes a certain proportion of non-firm energy, i.e. that which is not available in the dry years. In any given hydro-electric project the available energy is more or less fixed by the run-off, the principal variable being the installed capacity of plant. Hence changes in the average annual load-factor of a particular project usually mean changes in the installed capacity.

An approach to the study of the optimum installed capacity of a hydro-electric project calls for many data additional to the hydraulic features of the particular scheme. First, it is necessary to consider and bring into account the transmission system. Secondly, it is necessary to study the system demand and load curves, both at the present time and as estimated for the future. Thirdly, it is necessary to consider what other hydro-electric projects are likely to be developed in the future and how they can best be fitted in with the project under immediate consideration. Such studies require to be combined with corresponding studies of the complementary thermal plant.

A full investigation therefore presents a complex problem, and in practice it may be feasible to achieve only approximations to optimum design. It remains, however, highly advantageous to obtain the most accurate approximations possible with the available data.

(2) DEVELOPMENT OF A COMBINED HYDRO-ELECTRIC AND THERMAL SYSTEM

(2.1) The Problem of Installed Capacity

The capital cost of hydro-electric power can be considered as made up of two parts: expenditure upon the main storage works and associated aqueducts, and expenditure on tunnels, pipes, buildings, plant and transmission. The storage works are not directly dependent upon the installed capacity of the plant and may in the simple analysis be regarded as independent of the maximum rate of flow through the machines. The tunnels and pipes are designed to pass the full-load flow required by the machines, and their cost is thus directly connected with the selected plant capacity. The capital or annual costs of a particular installation therefore consist of a fixed amount representing storage and an amount which varies with the plant capacity.

The cost of storage usually forms a large proportion of the total cost of a hydro-electric installation, and the capital cost per kilowatt decreases as the amount of installed plant is increased. It will be found that for most projects the incremental cost of increasing the plant capacity, together with the provision of larger conduits and transmission, is less than the capital cost of increasing the installed capacity of a thermal station.

In countries where hydro-electric power resources predominate and where fuel is costly, it is probable that the comparison of generation costs will favour a hydro-electric project over a wide range of installed capacity. Decisions regarding the design of the hydro-electric stations will nevertheless involve a detailed study of the estimated cost of production and transmission of power for different installed capacities at the various possible sites. Such a study is, of course, subject to the overriding consideration that the total firm power and energy from the hydro-electric plant and any thermal plant can be satisfactorily combined so as to meet practical operating requirements.

If the seasonal variations in run-off do not conform with those of the power demand, as for example in a country where the water is derived largely from melting snow in spring, or where a heavy demand for irrigation pumping arises in dry weather, or where long-period droughts can occur, it may be that the storage required to produce a reasonable proportion of firm energy is either impracticable or excessively costly. Additional thermal plant may then have to be added to cover the deficiencies of the hydro-electric stations, and this will be operated (probably on a base-load regime) in times of water shortage. Some thermal plant is nearly always essential for full exploitation of hydro-electric resources and has been found necessary even in countries particularly well endowed with water power.

A problem of special interest from the planning point of view arises where a large proportion of the plant is necessarily thermal. With continued growth of load all countries will increasingly tend towards this condition, and further consideration will therefore be confined mainly to such circumstances, although the principles involved apply also to other conditions.

In a predominantly thermal system it will usually be preferable, for the reasons already given, to develop such water power as can economically be justified in comparison with thermal power with the greatest installed capacity, i.e. the lowest firm load-factor which the system can accept in conjunction with the more or less fixed amount of energy. Furthermore, an increase of plant capacity permits the spilling of water at times of high run-off to be reduced, resulting in better utilization of the available water and economy in the use of fuel by the thermal plant.

(2.2) Practical Limitations to Low-Load-Factor Operation

In a purely thermal system the machines will, so far as possible, be brought into operation sequentially in ascending order of their fuel cost per kilowatt-hour sent out, which generally results in the oldest and least efficient machines running on peak load only. In terms of the load/duration curve this means that in an expanding system new high-efficiency plants will be brought in at the bottom, making all older plant take progressively higher positions in the curve, until eventually each becomes peak-load plant. So long as the increase of efficiency of thermal plant continues, this process results in a maximum reduction in the average fuel consumption for the system.

It is not possible, however, to achieve the theoretical optimum use of plant in practice; factors such as reduced availability of base-load plant, lack of flexibility of peak-load plant, transmission limitations and operating difficulties (such as a tendency to run up the peak-load plant sooner than is necessary) result in the less-efficient stations generating more than their theoretically desirable quota and the more-efficient stations generating less. Fig. 2 shows a typical annual load/duration curve, with superimposed on it the blocks of energy generated by different plants grouped in order of fuel costs per kilowatt-hour sent out. The

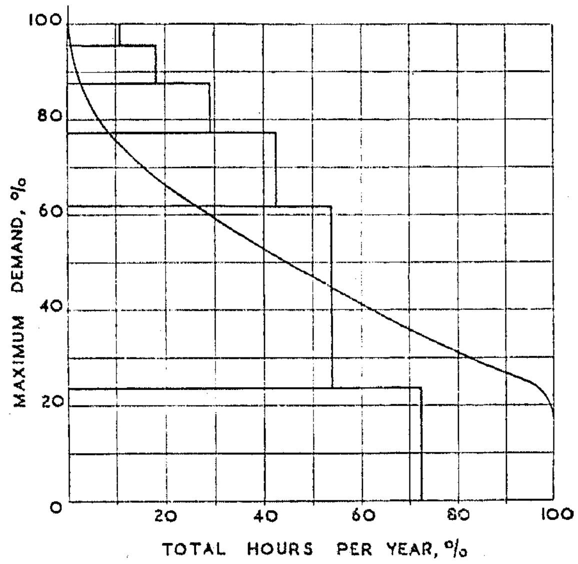

Fig. 2.—Typical annual load/duration curve, showing energy generated by different blocks of plant.

problem can also be illustrated by integrated duration curves (Fig. 3), the slope of which is proportional to the load factor of the various blocks of power. Curve (*a*) corresponds to the load/duration curve with the ideal operating condition of the

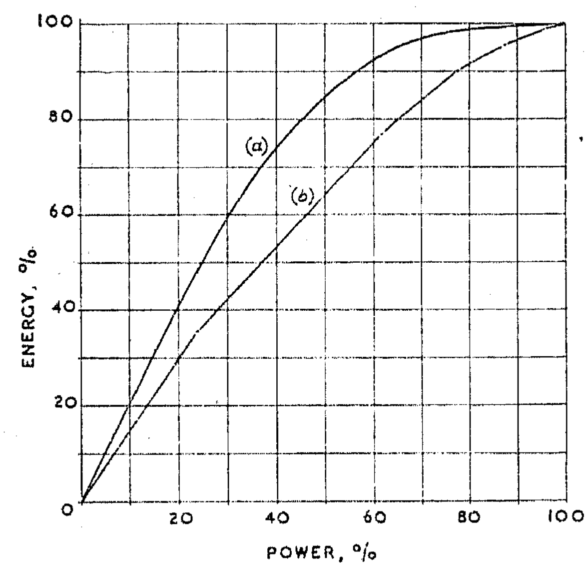

Fig. 3.—Integrated duration curves.

base-load machines generating their full desired quota of kilowatt-hours. Curve (*b*) represents what is actually achieved in practice, as indicated by the rectangles in Fig. 2.

For the purpose of settling the maximum practical installed capacity of a hydro-electric project, the conventional annual—or even monthly—duration curve is inadequate, as it gives no indication of day-to-day load conditions which the plant must be designed to meet; it is necessary to consider daily duration curves. In Fig. 4, P is the day of annual maximum demand and the remaining curves represent other typical days of the year. Some of such typical curves would refer to extremes of peak load and others to more favourable conditions obtained in better weather, the probable range of variation being determinable statistically. The normal type of annual duration curve is produced by integrating the areas of the individual daily curves enclosed by a series of horizontal lines such as AA and BB. Only on days P and Q does any load fall within these limits, and if a duration curve produced in this way were used as a guide to system operation the conclusion would be that some plant ought to run on those days only and be shut down on all other days of the year. This is not possible in practice and hence is misleading as a basis for judging results or forecasting the future.

There is no definite criterion for deciding how much energy

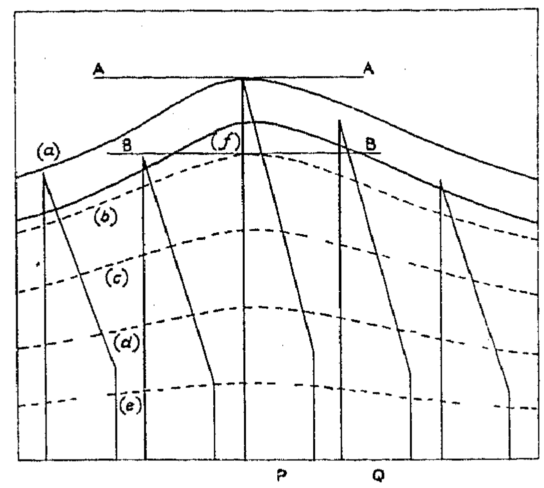

Fig. 4.—Basis of adjusted load/duration curve.

(*a*) Maximum demand (m.d.).
(*b*) 80% m.d.
(*c*) 60% m.d.
(*d*) 40% m.d.
(*e*) 20% m.d.
(*f*) Minimum demand.

the plant which generates a particular element of load on the day of annual maximum demand should generate on other days, but integration between curves such as (*a*) and (*b*) is a reasonable assumption. This implies that peak-load plant which carries the top $x\%$ of the load on the day of annual maximum demand should be capable of carrying the top $x\%$ on any other weekday when weather or other conditions lead to an extreme peak for that time of the year. Fig. 5 shows a duration curve of the

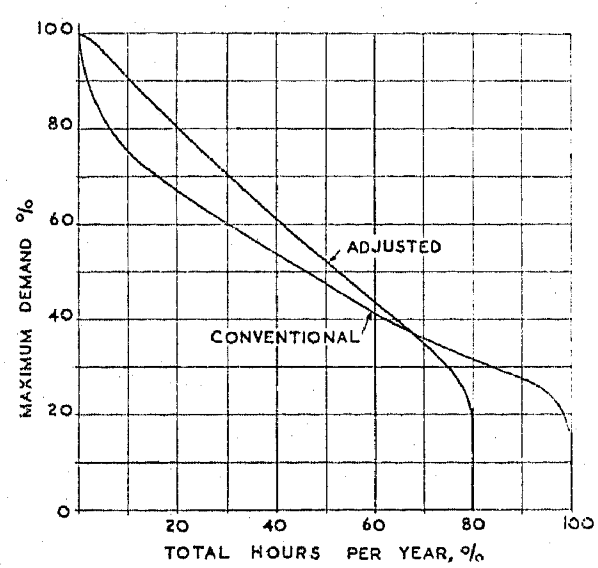

Fig. 5.—Conventional and adjusted load/duration curves.

conventional type, and superimposed is the adjusted curve of the type obtained by integrating between the curved lines in the manner illustrated by Fig. 4.

The importance of the adjusted curve in Fig. 5 is that it provides a more realistic starting-point in assessing the lowest acceptable firm annual load-factor (or the maximum acceptable installed capacity) for any given block of energy. It still remains necessary, however, to allow in each particular case for factors such as transmission limitations and lack of operating flexibility, which tend to increase the acceptable load-factor. The latter will be of less importance with hydro-electric peak plant than with thermal plant.

(2.3) The Introduction of Low-Load-Factor Hydro-Electric Plant

(2.3.1) System Operation.

Hydro-electric plant has a higher availability than thermal plant, even though this is reduced to some extent by the longer transmission which is usually involved. It is more flexible because it can be started, synchronized and brought up to full

load much more quickly. For example, the whole capacity, 102 MW, of the Galloway scheme in Scotland can be brought on in about 15 min, even if the call is made when the penstocks and turbine casings are empty and even though this capacity is contained in eleven machines. The time is less if the casings are already full. It is possible to change load rapidly, and in consequence the load variations can be followed more closely by the peak-load plant.

Hydro-electric plant, therefore, is especially suited to rapid load fluctuations, and its use in this way benefits the operation of the system as a whole. The thermal plant will be working on a more constant load without sudden fluctuations and this makes its operation easier. It must be remembered, however, that achievement of the design load-factor of hydro-electric plant is dependent on sufficient storage being provided to regulate annual flow; i.e. the assumed hydro-electric output must be firm, otherwise it might be necessary for thermal plant to be brought in at certain times to cover a deficiency of the water power, and the latter could not then be regarded as fully replacing an equivalent thermal capacity. In wet weather the water power can be generated at a load factor higher than that designed, thus saving fuel. Consequently, in a combined system, temporary departures from design operation will be desirable and will result in overall economy, whereas any departures in the all-thermal case produce an overall loss.

(2.3.2) Overall Fuel Consumption

The introduction of hydro-electric plant at the top of the duration curve has four important effects on the total fuel consumption on the system:

(*a*) The fuel which would have been needed to generate the actual hydro-electric output is saved.

(*b*) The fuel which would have been needed, owing to banking or other standby losses, to keep the equivalent thermal plant available for peak-load operation is saved.

(*c*) The quality of operation in the peak region is improved, because the hydro-electric plant is capable of following more closely the moment-to-moment variation in demand. With thermal plant it is more difficult to restrict the inefficient plant to minimum generation, and there is a consequent tendency to generate too much from the least efficient, and too little from the more efficient, plant. It may, in fact, often be difficult to restrict a peak-load thermal station to an annual load-factor of less than about 15%.

(*d*) There is a temporary loss of the chance to improve the average thermal efficiency which results from the addition of new thermal plant, whose efficiency would be higher than the average of that existing.

Factors (*a*) and (*b*) can be fairly closely calculated and (*c*) can be estimated, but (*d*) is more complex. To assess the ultimate effect it is necessary to study two alternative systems, one all-thermal and the other with a proportion of water power taking its place at the top of the duration curve. The analysis has to be in considerable detail and taken over a period of 25 or more years. The accuracy with which this can be done depends on ability to forecast the rate of system load growth, the annual improvement in efficiency of thermal plant and the trend in the price of coal; it also depends on assumptions which have to be made as to the life of thermal plant before it is removed from service as obsolete. Although such an analysis may not be feasible except as a rough approximation, it should be possible to reach a reliable conclusion as to the existence of an operating economy or loss, if not its magnitude.

(2.4) Freedom to Modify Design Load-Factor

The annual load-factor of a thermal plant can be varied as desired within certain limits, but the design load-factor of a hydro-electric installation (which fixes not only amount of plant but also size of tunnels and pipelines) must be determined as a result of economic studies before the scheme is designed. New circumstances which cannot readily be forecast may make a change in design load-factor desirable, and any freedom to do so in the future may be of considerable value. It will not usually be possible to reduce the load factor, i.e. to increase the plant capacity, unless some special provision is made when the scheme is designed and constructed. If the resources of a country are such that thermal plant must predominate, a hydro-electric plant designed for a particular load-factor will gradually tend to take a lower position on the duration curve as the system develops. There may be justification later for its position being raised, or at least kept where it was initially, by an increase in the plant capacity.

In low-head installations where the power station is at the foot of the dam, there may be comparatively little difficulty in constructing the foundations, short penstock and intake, and if desired, an extension to the power-station building for further machines to be installed later. With higher-head plants, where a tunnel, surge shaft and one or more pipelines are required, there is not the same scope for later extension of capacity and the difficulty and cost of constructing a new tunnel and pipeline may make the provision of additional plant impossible. The more economic course would probably be to construct all the water conduits for a larger capacity than it was intended to install initially. The incremental cost of doing this could be expected to be small relative to the incremental cost of thermal plant, and under the circumstances here considered it would be wise to look well ahead at the planning stage and consider what, if any, provision should be made for increase of capacity as the system expands. The particular case of the Tennessee Valley Authority may be mentioned as illustrating such a method of development. In the first 10 years the Authority installed 1 000 MW of hydro-electric plant, but during the second 10 years they installed a further 1 500 MW of hydro-electric plant and 1 500 MW of thermal plant.[2] The Authority have almost reached the limit of their potential and economic water resources, and to meet heavy new demands arising from a large atomic-energy project and other industries they are now constructing base-load thermal plants and have installed extra machines in spare bays provided in many of the existing hydro-electric plants.

(2.5) Increase of Firm Hydro-Electric Power

The proportion of the total mean annual output of a single hydro-electric plant or group of plants which can be regarded as firm, i.e. guaranteed in the driest year, is dependent on the amount of storage provided. The balance of the mean annual output is secondary energy which has a smaller value. Fig. 6 shows, for a

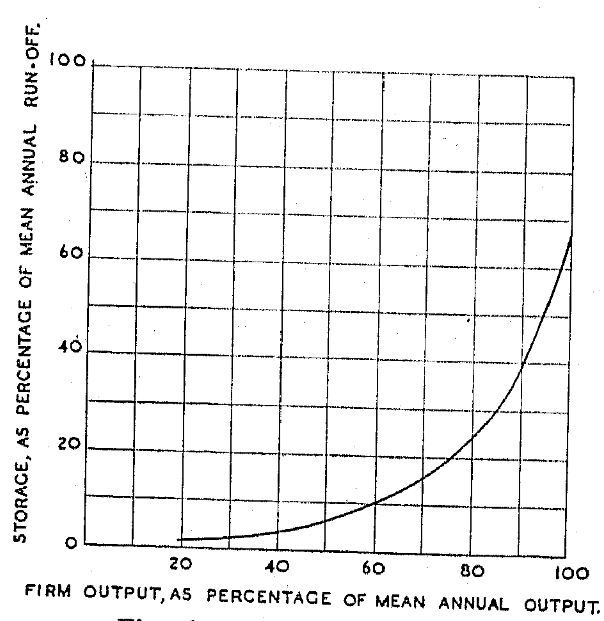

Fig. 6.—Reservoir storage curve.

typical annual load curve, the percentage of the mean annual output which can be regarded as firm for a particular storage capacity; the curve relates to typical conditions of run-off in Scotland and would not necessarily be applicable in other countries. If the whole of the annual output could be made firm the maximum benefit would be obtainable, but it is evident that above about 80% firm output the amount of storage required rises very rapidly, and an increase beyond this point is possible only where exceptionally favourable conditions exist. Thus for any particular reservoir site there will be some firm output which it is not economic to exceed by increasing the size of the dam.

Where storage is limited this may, in effect, mean that a certain acceptable load factor can be guaranteed throughout part of the year but not all of the time. Either the doubtful period must be eliminated by reduced installed capacity, or some means of firming must be provided. Two such means are possible, namely the installation of thermal plant especially for firming the water power and the use of pumps. Either method can be regarded as a means of augmenting the effective capacity of a reservoir, thus increasing the percentage of firm power, or as a means whereby the reservoir capacity can be reduced for a particular amount of firm power.

The use of thermal plant for firming is expensive, but may be justified; the use of storage pumps is a relatively new development, but considerable attention is now being given to this possibility, particularly in America. Of course, essential requirements are a tailrace pond from which to pump and a source of off-peak energy for pumping An energy loss of some 33% will be incurred, but pumping may be infrequent and the total amount of energy involved comparatively small. Moreover, the cost per unit of energy for pumping supplied at off-peak hours will be less than the value per unit of the stored energy if resold in peak hours.

As an example of this use of storage pumps, assume that the mean annual output of a hydro-electric project is 200 000 MWh and that storage representing 12·5% of the mean annual output can be economically provided, but that site conditions are such that it is impracticable for this amount of storage to be exceeded. Fig. 6 shows that the firm output would be 63% of the mean annual output, i.e. 126 000 MWh. If it is assumed that the particular installation is to be designed for an annual load-factor of 24%, the firm capacity which could be installed would be 60 MW. However, if the firm output could be increased to 75%, i.e. to 150 000 MWh, the capacity which could be regarded as firm for the same annual load-factor could be increased to 70 MW.

From Fig. 6 the storage required for this increased firm output would be about 20%, and water equivalent to 7·5% of the mean annual output would have to be returned to the reservoir in the driest years. Although such years may be infrequent, additional pumping will be inevitable owing to inability to predict the weather. The cost of pumping may nevertheless be unimportant, because pumping losses are likely to be largely (or wholly) balanced by the difference in value of the off-peak and the on-peak energy. The capacity of the pumps will depend on the deficiency of natural storage and on the number of off-peak hours during which energy for pumping can be supplied at a favourable cost. Once the required pumping capacity has been derived, the annual charges on the estimated extra cost of the installation can be compared with the additional benefit obtainable from the increase of firm power and energy.

An advantage of this use of storage pumps is that the level in the reservoir can be maintained higher during periods of low run-off than it would otherwise be and the falling off of capacity due to decreased head can be reduced. This is an important advantage, and in addition the flexibility of reservoir operation is enhanced.

The reversible pump-turbine referred to in Section 6.3 is ideally suited to such a purpose. The cost of the machine is greater than that of a conventional turbo-generator, but the considerable extra cost of a separate motor-driven pump, penstock and building can be avoided. The sacrifice of efficiency of generation which is to be expected may well be acceptable on one machine in a multi-unit station in exchange for the benefit obtained. Considerable research on this type of machine has been undertaken in recent years and some notable installations are now planned for construction. The machine for Hiwassee Dam (see Section 6.3) is an example; this machine is in lieu of a conventional unit and will be erected in a spare bay constructed when the power station was built.

The authors regard this use of pumps as an important development and think that in the planning of any storage project where there is a tailpond the possibility of having one or more pumps or reversible machines should always be considered.

(3) PUMPED STORAGE

If nature does not provide the conditions for low-load-factor hydro-electric developments, it may be possible to manufacture them, to produce a pumped storage scheme. This, in the daytime, has all the features already described of a low-load-factor scheme and the same advantages and disadvantages in its impact on thermal generation. The difference is that, during the night and perhaps at week-ends, pumps have to be operated to put back from a tailpond the water which has been used in the generating periods. Pure pumped storage can therefore be regarded as the ultimate development of firming by pumping as described in the previous Section.

In a predominantly hydro-electric system there may be low-head run-of-river stations where water cannot at certain times be used or stored and hence must be regarded as surplus. Under such conditions the incremental cost of supplying power for pumping will simply be the extra running costs of the generating plant and the similar costs on the storage plant, which will be very small. The comparison is therefore between the fixed annual charges of the storage scheme and the fixed charges plus the running cost of any alternative method of generation of equal output.

If hydro-electric plant does not predominate on the system there may be no water power which can be regarded as surplus, since by correct operation it should be possible to absorb secondary energy into the system with a saving of fuel at the thermal stations. In such a case, which is the more usual, the pumping energy must be supplied from the thermal stations. The overall efficiency of dual conversion of pumped-storage energy is not likely to exceed 66–68%, excluding transmission-line losses, and hence loads can be supplied only at about two-thirds of the efficiency of direct generation. It is not possible to use the most efficient thermal plants, as they are already running at their highest possible load-factor, and supply from other stations with rather lower efficiency must be assumed. If, for example, the incremental efficiency of the plant which can supply the pumping energy is 0·28, the equivalent efficiency of the storage plant will be $0 \cdot 67 \times 0 \cdot 28$, or 0·188. A thermal plant with such efficiency would be used only at a very low load-factor, and so the storage plant is necessarily placed high on the duration curve.

The pumped-storage plant and a natural low-load-factor development are similar in their effect on the overall fuel consumption of the system, except that the storage plant has the additional handicap of the cost of the pumping energy. This is

simply another factor which must be taken into account in the economic study of the all-thermal system and the alternative with a storage plant included. Such a study, taken over 25 years or more, indicates that, initially, after introduction of the storage plant the overall fuel consumption will be increased, but that the increase will diminish with passage of time owing to the effect of retarded improvement of thermal-plant efficiency lessening as the load factor of the "displaced" thermal plant decreases, i.e. as it is pushed up the duration curve by still later plant. Over a long period the total of all the effects mentioned seems to be almost zero, with possibly a very small saving of fuel in the alternative using a storage plant. This being so, it is considered that, if the capital cost of a pumped storage plant is less than the cost of a new thermal plant, the former is almost certain to give an overall advantage, bearing in mind that the sinking-fund charges are less for hydro-electric than for thermal stations.

Considerable flexibility is possible in the planning of a storage scheme. If the installed capacity and the daily load-factor are predetermined and it is practicable to provide the amount of storage necessary, the daily pumping period and the capacity of the pumps can be varied to give the best results. It can either be arranged that the water used in generation each day is returned to the upper reservoir during off-peak hours of the same day, i.e. a daily storage cycle, or a weekly storage cycle can be adopted wherein the reservoir is not fully replenished each day and a cumulative lowering is accepted, the reservoir becoming empty at the end of the week's generation. It is then refilled by pumping at the week-end. The daily cycle involves longer pumping hours each night, and it may be that the required period exceeds the time for which efficient thermal plant can be used to supply the pumping energy. If so, the pumping cost will be higher because less efficient thermal plant will have to be used. The pumping period can, of course, be reduced by increasing the pump capacity. A weekly storage cycle enables the pump capacity and daily pumping period to be reduced, but it necessitates a larger reservoir. The three variables of pump capacity, pumping period and reservoir capacity, i.e. size of dam, must be considered if the most economical scheme is to be achieved. An example is given in Section 11; it is hypothetical, but is based on estimates made for a storage project in Great Britain.

The Ontario Hydro-Electric Power Commission are constructing a large storage project supplied from surplus water power in conjunction with the new Sir Adam Beck Power Station on the Niagara River below the Falls. Under an agreement between Canada and the United States the balance of the water over and above that passing over the Falls is divided almost equally between them. The quantity which is to be allowed to pass over the Falls is greater in the summer daylight hours than at nights, for tourist reasons, and thus a greater quantity is available for power during summer nights than in the day-time. The project will utilize the surplus water at nights in the new generating station to provide power for six reversible pump-turbines. The main station is supplied by tunnel and open canal, and the pump-turbines, installed in a separate station, will pump from this headrace canal into an artificial reservoir. The same machines will pass the water back into the canal and produce about 220 MW during peak-load periods. This water will be used a second time in the main station, where an additional 300 MW will be installed for peak-load purposes only, making a total of 1 200 MW.

(4) NUCLEAR AND HYDRO-ELECTRIC POWER

The present intense interest in the development of nuclear power naturally raises the question of the probable effect of nuclear power stations on future hydro-electric projects. It is generally agreed that nuclear power stations are not likely to become commercially significant for a good many years; on the other hand, large hydro-electric projects have to be planned many years ahead and will have an assumed life (for amortization purposes) of more than half a century. Thus, even at the present time and despite lack of experience in the construction and operation of nuclear power stations, it has become necessary to consider their probable effect on proposed hydro-electric schemes.

It is expected that the first of the British experimental nuclear power stations will be in operation within two years, and it is significant that the anticipated overall cost of generation is of the order of 1d. per kilowatt-hour, which may well be regarded as a surprisingly low figure for the first experiment in a totally new field. One of the principal characteristics of present nuclear fission research is the embarrassingly large number of possible designs of nuclear reactors. The fact that there are so many possibilities is a fairly clear indication that the cost of nuclear generation is likely to fall substantially with the acquisition of greater knowledge and experience.

While it is not possible to assess the cost of nuclear generation in, say, 10 or 20 years' time, it is worth considering certain probable characteristics of such stations:

(*a*) For safety reasons, nuclear stations are likely to be placed in remote districts and will therefore require long-distance transmission. In this respect they will be similar to most hydro-electric stations.

(*b*) Nuclear power stations are likely to involve relatively high capital costs and relatively low running costs, and again there is some similarity with hydro-electric plants.

(*c*) For technical reasons it will probably be desirable to keep the loading of nuclear power stations comparatively constant. They are not likely, therefore, to be suited for peak-load operation and will not have the flexibility in operation which is characteristic of hydro-electric stations.

Any form of generation which has high capital costs and low running costs, but is capable of continuous operation, will obviously be most economic if operated as nearly as possible at 100% load factor. For this reason nuclear stations are likely to be operated for base-load purposes and will become less economic if and when all base-load has been supplied and further development might therefore have to be at lower load factors.

At this stage it may possibly pay to convert the base-load characteristics of nuclear power stations into peak-load characteristics by means of pumped storage, either in the form of pure pumped-storage schemes or in the form of low-load-factor hydro-electric projects augmented by the provision of pumping equipment.

This is looking far into the future, however, and the immediate question is whether the prospects of cheap nuclear energy might make it advisable to postpone hydro-electric development and, in place, build shorter-life thermal stations. The argument would be that such thermal stations would involve less immediate capital expenditure and would be nearing the end of their lives by the time nuclear power stations were fully commercial. Such a policy would, however, involve higher total generating costs initially, assuming that the postponed hydro-electric schemes were attractive in comparison with thermal generation.

On the basis of present knowledge such a policy would seem imprudent. In the first place, expectations regarding nuclear stations may not be realized for considerably longer than at present anticipated. Even on the most optimistic assumptions it is likely to be at least a decade before the costs of nuclear energy fall below those of coal-fired energy, and it may be still longer before nuclear stations compete with hydro-electric stations. In the second place, there is the ever-increasing

necessity in this and other countries to husband limited coal resources. The prospect of base-load nuclear energy cheap in running cost does, however, tend to strengthen the arguments in favour of relatively low-load-factor development of hydro-electric stations. It may well be that such stations will prove complementary to future nuclear stations.

It is tempting to speculate as to whether some of the techniques of hydro-electric construction, particularly underground construction, will eventually prove of value for those types of high-speed breeder reactors which are not inherently safe. It would appear that safety might be achieved by deep excavation in suitable rock and that economy might also be obtained by use of natural rock in place of concrete for biological shields and other purposes.

(5) THE EFFECT OF RISING PRICES

There is a further factor which affects all hydro-electric development. During the past half-century there has been a fourfold increase in prices and a corresponding reduction in the value of money. There is a very general expectation that prices will continue to rise, and the view has even been expressed that gently rising world prices are desirable to ensure full employment. It certainly seems probable that the trend of the past half-century (and longer) will continue into the distant future, and it is of importance to consider what such an assumption implies in regard to investment in generating plant.

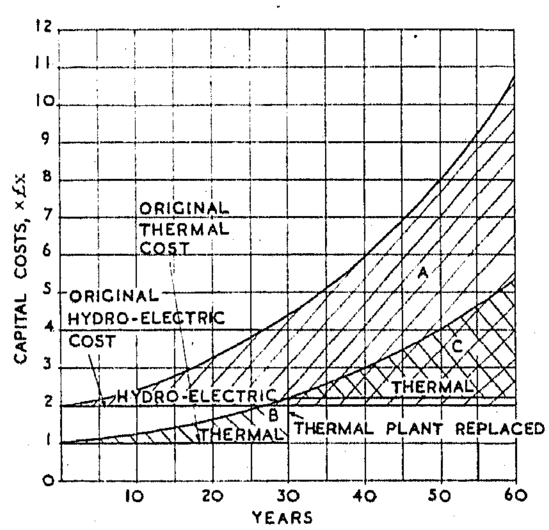

Fig. 7.—Comparison of relative price levels and replacement costs.

In order to illustrate the effects on thermal and hydro-electric plant investment, Fig. 7 has been drawn on the assumption that prices will rise during the next half-century or so at an average rate equal to that of the past half-century. Two alternatives are considered:

(*a*) Investment in a thermal station whose capital cost is £x.
(*b*) Investment in a hydro-electric station of similar installed capacity whose capital cost is £$2x$.

Both investments are assumed to be equally profitable initially, and the thermal station is assumed to have a life of 30 years and the hydro-electric station a life of at least 60 years. It is further assumed that construction is financed by loan capital repayable at par.

At any moment after year 0 the benefit in respect of capital investment will be related to the difference between the original capital cost and the capital cost of building an equivalent station at the date in question. The area marked A, which is the integration of the difference between the original and the replacement cost multiplied by time, can be regarded as being roughly proportional to the total benefit in respect of capital investment accruing to the owner of the hydro-electric station as a result of falling value of money. Areas B and C represent the corresponding capital investment benefit to the owner of the thermal station. The large excess of area A over areas B + C is indicative of the benefit which accrues to the equity owner of a large long-term capital investment such as a hydro-electric project. It must, however, be stressed that Fig. 7 is based on a number of assumptions and ignores various effects such as changes in interest rates and changes in replacement costs due to technological advance. It is therefore merely illustrative of the general effect on capital investment of rising prices.

From a national point of view, on the assumptions made, the gain which accrues to the owners of the plant will tend to be balanced by the losses incurred by those who lend money repayable at par, so that it would be false to draw the conclusion that long-term capital investment is necessarily in the national interest. Nevertheless, the relatively large benefit to the equity owners of long-life hydro-electric stations as compared with the benefit to the equity owners of the shorter-life thermal stations is striking—particularly when it is borne in mind that a large part of a hydro-electric station, e.g. most of the civil-engineering works, will not have to be replaced, even at the end of 60 years. As examples of this benefit mention can be made of the two Grampian Power Company stations (built about 1933) and the Galloway stations (built about 1936). The original capital costs of these works are now much lower than present-day costs, and the stations consequently contribute to keeping down the cost of electricity.

(6) HYDRO-ELECTRIC PLANT

(6.1) Water Turbines

There has been no significant change in the fundamental design of hydraulic turbines for general power development since the introduction of the movable-blade Kaplan machine more than 30 years ago. Development has been concentrated on improvement of efficiency, greater output, and higher specific speed and upper limit of head for each type of turbine.

The present levels of turbine efficiency are about 93% for Kaplan, 92% for Francis and between 90 and 91% for Pelton turbines. These figures can only be a general guide, because the maximum efficiency obtainable with any type depends on the specific speed of the runner. Higher figures have been published, but it may well be that these have been influenced by the inherent inaccuracy of the various methods of measuring water flow.

Reaction turbines still suffer, to a degree varying with the type and specific speed, from a drop of efficiency at maximum and at partial loads due to the use of guide vanes to regulate the flow of water into the runner. Experiments being carried out with a type of guide apparatus which will produce annular flow at the runner inlet could give rise to an important development, since by this means the present disadvantage of many moving parts and poor part-load efficiencies would be alleviated.

Turbine outputs have been gradually stepped up to the existing limits of 165 000 b.h.p. for Francis machines at the Grand Coulee power station and 111 000 b.h.p. for Kaplans at the McNary Dam. A contract for Francis turbines of 175 000 b.h.p. of British design has recently been placed by the Quebec Hydro-Electric Commission for their Bersimis station. Single-jet twin runner Pelton turbines of 150 000 b.h.p. are now being manufactured for Cimego power station in the Italian Alps, and 4-jet single-runner vertical impulse machines of about the same output are being installed in the Kemano station in British Columbia. This represents a considerable advance in output of impulse turbines. The continuance of this upward trend in capacity is a matter more of economics than of any technical or design problem. Although the cost per horse-power of the whole machine will normally be reduced as the capacity

increases, there is a limit beyond which the reverse will result and which can only be determined in each particular case. The optimum capacity is affected by problems of transport to site and erection and to some extent by the particular manufacturer's production facilities. It is probable that there will not be many future installations where such large-capacity machines as those mentioned are economically or operationally suitable, and it is unlikely that there will be much increase above these outputs.

The desire to reduce cost leads to higher speeds being adopted for a given combination of head and output. This results in the upper limits of head for Kaplan and Francis turbines being continually increased, so that the higher-specific-speed Kaplan turbine is used up to heads which hitherto had been considered technically practicable only for the Francis type; similarly, the Francis turbine encroaches into the high-head range of the Pelton. The highest heads for which Kaplan and Francis machines have yet been constructed are respectively 230ft at the Bort-Rhue plant in France and 1 490ft at Fionnay in Switzerland. The upper limit of head for a Pelton wheel is determined solely by the ability to obtain adequate strength of buckets and wheels; the highest existing head at present used is 5 800ft at Reisseck in Austria, and particulars of some of the highest-head plants of each type are given in Table 2.

Table 2

SOME EXISTING HIGH-HEAD TURBINES

Station	Country	Head	Output	Speed
		ft	b.h.p.	r.p.m.
Kaplan Turbines				
Bort-Rhue	France	230	31 500	375
Barcis	Italy	199	13 500	500
Requejada	Spain	188	5 700	500
Invergarry*	Scotland	177	28 000	250
Pollaphuca	Ireland	165	25 000	300
Ligga	Sweden	130	105 500	125
Lavey	Switzerland	125	30 000	214
Francis Turbines				
Fionnay	Switzerland	1 490	63 000	750
Limberg	Austria	1 430	77 500	500
Vinstra	Norway	1 360	69 000	500
Fiastrome	Italy	1 320	20 000	1 000
Lages	Brazil	1 100	54 000	600
Lardit	France	1 100	30 000	750
Pelton Turbines				
Reisseck	Austria	5 800	31 000	750
Dixence	Switzerland	5 700	50 000	500
Mieville	Switzerland	4 750	47 500	500
Pragnieres	France	3 920	100 000	428

* Under construction.

These advances have been made possible by the use of materials which have better resistance to cavitation and corrosion and also by the considerable research which is carried out in hydraulic laboratories and testing stations into the problem of cavitation and runner blade profiles. The use of stainless steel for all parts of a turbine subject to erosion can frequently justify the extra cost compared with plain carbon steel by saving outages for repair, particularly with medium- and high-head machines, and a stainless-steel runner can enable the depth of a machine relative to the tailwater level to be reduced, thus saving in cost of excavation of the foundations. A material containing 12–14% of chromium with not more than 1% of nickel is now favoured. Manganese bronze has been much used for turbine runners, particularly those of small dimensions, but aluminium bronze containing about 10% of aluminium and 1% of iron has even better resistance to cavitation; moreover, it has good tensile strength and can be welded.

In the choice of the most suitable speed for the machines for a particular installation—and the selection of the type of turbine if the conditions are within the overlapping range of two types—it is important to realize that the highest speed will not necessarily give the lowest overall cost of the installation. An increase of specific speed is usually accompanied by a lower maximum efficiency and a greater depth of excavation necessary for the draft tube; this is particularly so with Kaplan turbines. Thus the choice must be made with full knowledge of the incremental cost of excavation for the foundations and of the value of efficiency. Maximum efficiency may not be the main consideration, and weighted efficiency over the anticipated operating range of output is usually the more important criterion.

In recent years there has been a greatly increased use of steel plate and fabricated construction, which affords reduction in weight and therefore in cost, and welding has almost completely superseded riveting. Some manufacturers prefer to fabricate Francis runners whenever this is practicable, and thereby avoid the risk which always arises of castings being faulty. The welding of pressed-steel blades to a cast or rolled rim and a cast hub permits pre-machining of the rim and hub to smooth and accurate contours and gives a blade surface which requires little hand grinding. A fabricated Francis runner, however, is not necessarily cheaper than one of cast steel; this depends on the ability of the steel founder to produce a sound and accurate casting which requires the minimum of cutting, welding and grinding of flaws.

It is unlikely that there will be any major change in mechanical governor design in the future, although improvements in detail will doubtless be made. Extensive interconnection of power-supply systems and individual plants has changed the function of a turbine governor from that of pure speed control on an isolated system to that of a frequency/power regulator on the interconnected system. It must often be capable of control by any of several quantities, e.g. by frequency and output, water level, water flow or power flow in the interconnections, and it must be possible to mix these quantities and vary their relative magnitudes. In this respect the new electronic governor which has been developed in Sweden shows considerable promise. This embodies an electronic-valve regulator to operate the relay valve of the turbine servo-motor instead of the normal pendulum-operated linkage used in the purely mechanical governor. Its principle is the oscillating circuit comprising two balanced electronic valves in push-pull, a resonant circuit responding to frequency which is supplied from a tachometer-generator or voltage transformers on the turbo-generator, and an *RC* circuit to provide the damping and feedback which is supplied from a potentiometer operated mechanically from the turbine guide-vanes. The quantities mentioned above are all introduced electrically by potentiometers.

The common methods of measurement of water flow for the purpose of establishing turbine efficiency have an inherent inaccuracy, and an appreciable tolerance, usually accepted as 2%, is normally required by the manufacturer. Measurement at site involves an appreciable expenditure on equipment and outage of the machine being tested. Furthermore, tests can be taken only at the head available at the time, and if the machines are designed to operate over a large range of head the information obtained is not as complete as the owner usually requires. It is often necessary, therefore, to accept the machine on the basis of tests at one head and to use the manufacturer's design data for other conditions of head and output.

Because of this insufficiency, there has been an increasing use

of reduced-scale models tested under laboratory conditions; such models must be complete and entirely homologous with the prototype, and the scale will be such that the runner diameter is of the order of 500–650 mm. Complete information and reliable results can be obtained and the design can be modified in the light of model tests if these are completed at an early date. There is, however, doubt as to the accuracy of any of the usual scale-effect formulae used in calculating the absolute value of the prototype efficiency. The formulae have no exact theoretical basis and are derived principally from experiment on full-scale machines and homologous models. They can be interpreted in different ways, particularly their application to efficiencies at loads above and below the optimum, and it is important that the particular formula and its method of application are agreed between the purchaser and the manufacturer, preferably before a contract is placed.

Whether or not this method gives the true prototype efficiency over the whole range of tests, it does produce results which from the contractual point of view cannot reasonably be disputed and no tolerance need be granted. This may be important if a large bonus or penalty on guaranteed efficiencies has been agreed in the contract. Turbines can be accepted on the basis of guaranteed model efficiencies, thereby removing, from the contractual aspect, any doubt about the scale-effect formula. A complete model may cost as much as £5 000 to manufacture and test, but such expenditure may well be justified. However, unless manufacturers can have the opportunity of tests at site and on complete models, it will probably not be possible further to determine the most satisfactory scale-effect formula to be applied to the model results. Even so, the disparity between the results obtained by using different formulae is almost certainly less than the limits of the tolerance accepted on site-test results. An indication of this is given in Fig. 8; the curves show actual model

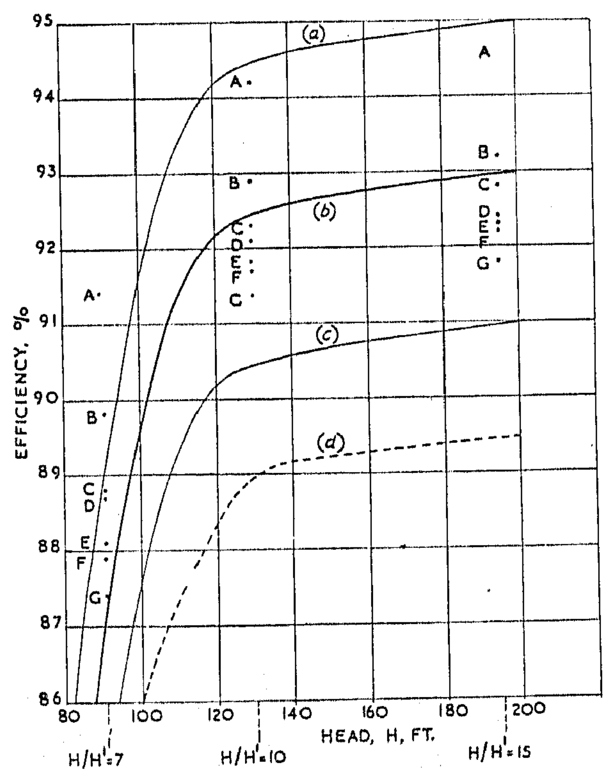

Fig. 8.—Model test and prototype efficiencies derived from different scale-effect formulae.

Model scale ratio = 5·23; model test head, $H' = 13$ ft.
(*a*) Upper tolerance limit for site tests.
(*b*) Guaranteed.
(*c*) Lower tolerance limit for site tests.
(*d*) Model test results.

test efficiencies at various prototype heads, together with the guaranteed prototype figures and the limits of a $\pm 2\%$ tolerance for site testing. The points numbered A–G, which are shown for three ratios of prototype head to model head, are the prototype efficiencies derived from the model results and seven of the various formulae which have been produced. If point A, which is exceptionally high, is disregarded, it appears that in this particular example the remaining six points fall within a range of efficiency of about $1\frac{1}{2}$–$2\frac{1}{2}\%$ (absolute). It must be stressed, however, that the figures given relate only to optimum efficiency at each head; the curves do not take into account efficiencies at part-load or overload.

(6.2) Generators

Developments in design of vertical-shaft generators have been fully described in recent papers.[12,13] The tendency for turbine outputs and speeds to be increased naturally reflects on the generator. With low-speed machines, having a rotor peripheral speed at normal running below about 15 000 ft/min, the problem of increased output is principally one of transport to site and erection. Generators having rotor diameters between 30 and 40 ft and running at only 75 r.p.m. exist, and it is usual for such machines to be taken to the site in pieces as large as can conveniently be transported, and then erected at site for the first time. This means that certain tests which it is practicable to carry out only in the manufacturer's works cannot be made. Provided that the generators are designed for initial erection at the site, there should be no difficulty with low-speed machines of providing such outputs as are likely to be required in the future.

With high-speed generators the problem is more that of the mechanical design of the rotor poles and coils to withstand the centrifugal stresses due to increased runaway speeds which are entailed by higher turbine specific speeds. However, the large outputs of high-speed machines recently built are well below what is attainable; the peak occurs in the speed range 400–600 r.p.m. and exceeds 200 MVA.

The demand for an increased rate of exciter response and restriction of voltage rise on load rejection is leading to the replacement of the rheostatic excitation-control system by one of an electronic type from which much closer voltage regulation is obtained. Systems have been developed which are fundamentally similar in that the normal vibrating-contact or sector-type automatic voltage regulator is superseded by a magnetic amplifier and the pilot exciter is omitted.

(6.3) Reversible Pump-Turbines

Mention has been made earlier of the reversible pump-turbine. A reversible machine of the propeller type was installed in Germany about 20 years ago, but as such a machine is restricted to operation with a head within the range of a Kaplan turbine, its general use in pumped storage schemes is limited. Considerable research and model tests have been carried out in recent years on reversible machines with runners of the Francis type which could be used up to much higher heads. Such a machine must have a runner design which is a compromise between that best for a pump and that best for a turbine, since one speed cannot be the most suitable for both operations. The machine will be larger than a conventional Francis turbine of the same specific speed but smaller than a normal pump. A notable machine of this type will be installed at Hiwassee Dam of the Tennessee Valley Authority. According to published information, it is designed to deliver 3 900 cusec against a head of 205 ft when operating as a pump and requires an input of 102 000 b.h.p. Nominal rating when operating as a turbine is 80 000 b.h.p. at 190 ft head.

It is likely that there will be an appreciable demand for a reversible machine, and there would seem to be scope for further technical advance. An alternative to the compromise runner design is to have a 2-speed electrical machine, one speed for generation and a higher speed for pumping. For low heads a

further alternative is a Kaplan-type runner with blades which could be reversed for pumping without changing the direction of rotation of the machine.

(6.4) Control of Plant

The control of hydro-electric plant was the subject of a paper[14] presented to The Institution a few years ago. The alternative methods can be classified as fully manual, semi-automatic and fully-automatic control. Opinions of operating authorities vary on the relative merits of these methods. Some do not favour semi-automatic control, because trained staff are required in the turbine room and it is thought desirable that they should be more fully occupied with the machines than is required by push-button semi-automatic operation; others consider that fully automatic control is a complication and wish to avoid the extra maintenance of a specialist nature which it involves.

From the operational aspect, fully or semi-automatic control enables machines to be started in the shortest possible time, and thus the inherent advantage of hydro-electric over thermal plant in a combined system (of rapid starting and stopping) can be fully utilized. From the economic aspect, the extra cost and maintenance of the control equipment and supervisory cables has to be compared with the cost of the salaries and overheads of such staff as can be saved. In particular, for small and isolated stations it is to be expected that fully automatic control will show an appreciable saving.

It is probable that large base-load plants will continue to be staffed and be either manually or semi-automatically controlled, but it seems likely that the use of fully automatic remote control for smaller peak-load plants will be extended, especially when they are situated in lonely and intractable country.

(7) TRANSMISSION AND INTERCONNECTION

Good hydro-electric sites are frequently remote from large load centres, so that the electrical transmission of their output over long distances is often a necessity. In the past, technical inability to transmit over the distances involved has been a deterrent, but recent development of transmission technique has brought within reach more and more of the cheap but remote sources of water power throughout the world. In many cases their exploitation is being speeded by mounting prices or shortages of fuel.

From the aspect of deciding how a given water-power scheme should be developed, or whether it should be postponed in favour of some alternative, the costs of the scheme itself and the necessary transmission are inseparable and must be the basis of economic studies such as are referred to in Section 2. Large hydro-electric schemes, particularly if remote, may call for very high voltages and the consequent use of multiple or "bundled" conductors to reduce corona loss and reactance, but there are a number of other methods whereby the load capacity of long lines may be increased. These are mainly directed towards compensation of the line reactance and capacitance and the maintenance of transient stability, and include the following:

(*a*) High-speed switching.
(*b*) Intermediate switching stations in double or multiple-circuit lines.
(*c*) Rapid control of generator excitation.
(*d*) Shunt compensating devices in the form of synchronous condensers or reactors.
(*e*) Series capacitors.

All of these methods have been recognized for many years, at least in theory, but it is only comparatively recently that the need for their co-ordinated use has resulted in the technical development work, both theoretical and practical, being carried out.

The collective effect of all the foregoing methods of improving a.c. transmission is so considerable that, for the present at least, there is no great urgency to develop d.c. transmission in those areas where a.c. overhead lines can be constructed. D.C. transmission offers the possibility of transmitting very large blocks of power over distances beyond the likely capacity of a.c. transmission, even at much higher voltages than at present in use. Such transmission may therefore become of importance in the future, although the prospect of this for overhead routes now seems more remote than at one time was thought probable. It seems likely that d.c. transmission will in the first instance be developed for submarine or underground routes, where its advantages are so outstanding. One such case is the proposed link between Great Britain and the Continent[17] which, although likely to be an a.c. system initially, may later be greatly increased, and possibly cheapened, by the use of d.c. cables.

The selection of the best transmission system for any given hydro-electric project or group of projects involves such fundamental assumptions as future fuel prices, life of equipment, rates of load growth, probabilities of outage, etc. Some of these may be little more than guesses, so that it is not usually possible to arrive at one clear answer by calculation. A careful study, however, enables definitely unsuitable alternatives to be eliminated, leaving the final choice to be based on judgment and experience.

Within the boundaries of a sovereign State, adequate transmission and interconnection of capacity can be provided to achieve full integration of hydro-electric and thermal plant, and the benefits of such full integration can be very considerable. There is, however, the further possibility of interconnecting the systems of two or more adjacent countries, thus reducing the required amount of plant. This interconnection is likely to be particularly advantageous if the two or more countries in question vary considerably in characteristics. Such circumstances arise where one country has predominantly thermal generation and the other predominantly hydro-electric generation; but even if both have predominantly hydro-electric generation there may be important diversities arising from the differing characteristics of the stations. For instance, one country may depend upon winter rainfall, while another may depend upon the melting snows in spring and early summer.

The maximum benefit would be obtained if such countries were fully integrated in the manner possible within the boundaries of a single State, but for political reasons it is usually impossible for one sovereign State to be dependent upon another for vital supplies of electricity. Partial integration by means of high-voltage interconnection can nevertheless be of great advantage, even if the actual net interchange of energy is arranged to be approximately zero over a complete year. There has, in fact, been a rapid increase in the number of high-voltage transmission lines connecting one European country with another. In the particular case of France and Great Britain, recent investigations have shown that interconnection could result in a saving of plant amounting to some 300 MW.[17] This saving may more than offset the whole capital cost of interconnection, but political considerations may prevent its full exploitation, bearing in mind the criterion already mentioned that one State cannot afford to be wholly dependent on another. In other words, the reduction of installed plant in the two interconnected countries must not be so great as to leave either country seriously embarrassed if the interconnection is severed.

(8) CONCLUSION

The paper has been more concerned with drawing attention to the problems (and possibilities) arising in combined thermal and hydro-electric systems than with solving these problems.

To many of them there is no certain solution, mainly because of inherent lack of adequate data, particularly those relating to the future. This, however, merely means that maximum use must be made of such data as are available and that the problems must be approached with full knowledge of both thermal and hydro-electric operating characteristics. Difference of opinion between thermal and hydro-electric engineers as regards the design of projects is not uncommon and may arise because of inadequate understanding by the one of the problems of the other, or lack of mutual appreciation of the inherent characteristics of the two types of plant.

The starting-point in the design of a hydro-electric project is the hydrographical and civil-engineering data, but the final design must depend on the results of a study of the other problems and possibilities relating to combined thermal and hydro-electric operation. This is especially true where, for instance, there are possibilities of pumping or making provision for future increase in installed capacity, or where an exceptionally long transmission is involved. Consideration of the latter is necessary from the outset, since transmission cannot be treated as an independent problem.

Even on the assumption of the fullest use of all available data, and the most careful study of the various interrelated problems, it remains probable that the best which can be achieved is to reduce to narrow limits the range of uncertainty regarding the principal hydro-electric design features. The final decision within this range will then be a matter of judgment. If a particular project turns out to be marginal, or barely economic, it will be necessary to decide whether it is justified as a fuel-saving measure, or whether the probability of continued rise in prices and fall in money values should be taken into account. The effect of this factor can well convert a present marginal project into a highly profitable project in the future.

The technical development of hydro-electric plant has reached a stage where there is limited scope for further improvement in design and efficiency. Since the cost of civil-engineering works predominates in the overall costs of most hydro-electric installations, it is mainly in this field that improvements in design and construction methods can be looked to for any appreciable reduction in the overall cost of water power. Such savings as may be achieved in this respect in the future may well be offset by the need to develop power at sites which are increasingly less favourable. On the other hand, a continuation of the steady improvement in thermal-plant efficiency is likely for some years to come, but this may be more than counterbalanced by further increases in the cost of fuel.

The initial cost of thermal power can be estimated in advance within close limits and is largely independent of the location of the plant. The future cost depends on the price of fuel. The capital cost of hydro-electric installations must be estimated from a detailed investigation of each individual site and is not necessarily related to that of any other similar plant. Even after a careful survey, unexpected difficulties encountered with the civil-engineering works may arise and cause the original estimates to be exceeded. Thus, the cost of thermal power can be closely estimated at the time the plant is built, but is liable to unpredictable future variations. The cost of water power, whilst more difficult to assess in the first instance, remains virtually constant once the plant has been constructed.

(9) ACKNOWLEDGMENTS

The authors would like to acknowledge the invaluable assistance received from their colleagues in the preparation of the paper. They also wish to express thanks for data made available to them by various persons.

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(11) APPENDIX: COST ESTIMATES OF A PUMPED-STORAGE SCHEME

The example which follows serves to illustrate the flexibility which is possible in the planning of a storage project. The scheme envisages a single pumping stage between a large natural lake and an artificial reservoir in the surrounding hills. Approximate calculations and estimates are given in Table 3 for an installed generating capacity of 200 MW, and for three alter-

Table 3

ESTIMATED DATA FOR THREE PUMPED-STORAGE SCHEMES

	Scheme (a)	Scheme (b)	Scheme (c)
General Data			
Daily pumping period, hours	7	8	7
Type of storage	Weekly	Daily	Daily
Generating capacity, MW	200	200	200
Pumping capacity, b.h.p. $\times 10^3$	268	268	301
Storage required, for daily generation, ft$^3 \times 10^6$	91	91	91
Storage obtainable each day (full-load pumping), ft$^3 \times 10^6$	81	92	91
Deficiency each day, ft$^3 \times 10^6$	10	Nil	Nil
Extra pumping at weekend (Saturday and Sunday), hours	4½	Nil	Nil
Reservoir working capacity required, ft$^3 \times 10^6$	131	91	91
Energy			
Generated annually, MWh $\times 10^3$	286	286	286
Required for pumping, MWh $\times 10^3$	432	432	432
Delivered to point of supply, MWh $\times 10^3$	275	275	275
Losses, MWh $\times 10^3$	157	157	157
Power			
Delivered (less transmission losses), MW	193	193	193
Costs			
Capital (including transmission), £ $\times 10^3$	8 400	8 200	8 650
Annual:			
Capital charges, £ $\times 10^3$	404	396	420
Operation, etc., £ $\times 10^3$	20	20	20
Cost of pumping energy, £ $\times 10^3$	810	828	810
Total, £ $\times 10^3$	1 234	1 244	1 250
Revenue			
Sale of power, £ $\times 10^3$	772	772	772
Sale of energy, £ $\times 10^3$	745	745	745
Total	1 517	1 517	1 517
Annual surplus, £ $\times 10^3$	283	273	267

native proposals, (*a*), (*b*) and (*c*). Alternative (*a*) is based on a weekly storage cycle, with pumping restricted to 7 hours each night, whilst (*b*) and (*c*) cover a daily storage system, (*c*) having the shorter pumping period compensated by additional pump capacity. Both (*b*) and (*c*) have only 70% of the reservoir capacity of (*a*).

The following assumptions are made:

Mean generating head	600 ft
Mean pumping head	636 ft
Generating period	5½ hours per day, 5 days per week
Daily load factor	23%
Annual load factor	16%
Overall efficiency of conversion (including transformers)	67%
Transformer losses	2%
Overhead line losses	1½%
Interest on capital and on sinking fund	4%
Value of power	£4 per kW
Value of energy, on-peak	0·65d. per kWh
Value of energy, off-peak (for 7 hours)	0·45d. per kWh
Value of energy, off-peak (for 8 hours)	0·46d. per kWh

It will be seen that, in this particular analysis, alternative (*a*) appears the most favourable, but it is evident that the annual surplus is very sensitive to the assumed cost of energy for pumping. Thus the pumping period should be the longest each night for which the energy can be obtained at the lowest rate and there will be some period which it is not economic to exceed.

It may be that the plant will not be required to generate each day the maximum energy for which it is designed (as assumed in Table 3), in which case the annual surplus becomes greater, since, provided that the kilowatt earning capacity is always maintained, every kilowatt-hour generated represents, in this particular example, a definite financial loss. If, for example, only three-quarters of the maximum annual energy is produced, the annual surplus for alternative (*a*) becomes £299 000. It may be considered proper to allocate a proportion of the kilowatt capacity to the general system allowance for breakdown, in which case credit cannot be taken for the full installed capacity. If such allowance were 10% the revenue from sale of power, and hence the annual surplus, would be reduced by about £80 000.

The load factors in this particular example are higher than is often possible for pumped-storage schemes, and if lower load-factors were permissible the annual surplus would be greater.

DISCUSSION BEFORE THE JOINT MEETING OF THE INSTITUTION AND THE INSTITUTION OF CIVIL ENGINEERS, 6TH JANUARY, 1955

Mr. T. Lawrie: It is now over 26 years since Mr. Haldane's firm first advised on hydro-electric schemes with which I was concerned in the Highlands, and after many vicissitudes and lost opportunities there is now in the North of Scotland a large and rapidly-growing development of hydro-electric power. The outstanding advantage of this power is that it is distributed at reasonable prices to the sparse and scattered population of an important food-producing area and is exported as peak-load power to Central Scotland. Perhaps its most dramatic advantage is that it is saving 700 000 tons of coal per annum, or nearly a fortnight's production of the Scottish coal pits. This represents a hidden dividend of 5% on the cost of the hydro-electric schemes, in addition to what they earn as economic producers of electricity. Moreover, this coal saving will be doubled within the present decade as hydro-electric schemes now building come into production.

A third great advantage from the national aspect is that here at last is a first-rate hydro-electric shop window. Manufacturers of hydro-electric plant, civil engineering contractors and consulting engineers can now take potential customers from abroad to see the many dams, power stations and tunnels which have been built and equipped here at home in Scotland, and they can demonstrate in a practical way our ability to compete with European and American concerns in all the continents of the world and even, I am glad to say, by breaking into the United States market.

This is one point which the authors might perhaps have brought out, on grounds both of technical interest and of the impression which it will create at home and abroad. Table 1 gives the approximate proportions of thermal and hydro-electric plant in various countries, and in Scotland we really have a mixed thermal and hydro-electric system, as the following facts and figures show. In the Hydro-Electric Board's area in the North of Scotland, north of the Firth of Tay and the Firth of Clyde, there is a higher proportion of hydro-electric plant than there is even in Sweden, while in the whole of Scotland the

proportion of hydro plant is 50% greater than in the United States. The figures are as follows, for 1954:

	Thermal	*Hydro-Electric*
	%	%
Hydro-Electric Board's Area ..	22	78
Whole of Scotland	67	33

To take the matter even further, when hydro-electric schemes now under construction are completed towards the end of this decade, the proportions in the Hydro-Electric Board's Area will be 14% thermal and 86% hydro-electric.

I should like to describe the problems of hydro-electric design in the Hydro-Electric Board's mixed thermal and hydro-electric system and how they have worked out in practice. In the first place, Scotland's rainfall is much higher in winter than in summer, and the average monthly run-off into the Board's reservoirs follows very closely the average monthly demand for electricity. This is a great advantage, which offsets the disadvantage of our smaller catchments compared with Continental countries or our low heads of water compared with Norway and Switzerland; ample storage is nevertheless desirable, because of occasional severe freeze-ups in January and February. Secondly, the availability of hydro-electric plant is remarkably high, because power can be obtained quickly at the turn of a tap and because outages for repair and maintenance or because of breakdown are very small indeed—much less than for steam plant.

Those are the foundations on which we are operating in the North, and peak-load water power has been developed to a large extent in Scotland. It started with the Galloway scheme 25 years ago, which develops 102 MW at 20% load factor, and the Hydro-Electric Board have carried the idea further with their first large scheme at Sloy, 130 MW at 10% load factor, followed by two more schemes. Shira with 45 MW at 20% and Errochty with 75 MW at 15%, totalling some 250 MW at an average load factor of $12\frac{1}{2}$%. Some of this peak-load power is absorbed in the Board's own area and a great deal is exported to Central Scotland.

Fig. A shows, for a typical winter's day in 1952, how the extreme peak-load power exported from Sloy and the more moderate peak load from the rest of the Board's stations fit in to the total load curve of Central Scotland. The total load curve for Central Scotland is the line which goes over the top, and the peak-slicing operations are shown, first at the extreme peak and secondly at the moderate peak, enabling the steam plants to run at a constant load for roughly the eight working hours of the day. The steam plant in Central Scotland is thus enabled to operate with greater thermal efficiency at a steady load throughout the working day. In practice, the peak load exported to Central Scotland is a fixed maximum, at present 215 MW, and after allowing for this we have a further 216 MW of hydro-electric plant, mainly base load, and 121 MW of steam plant, providing the mixed system in the Board's own area, the successful combination of which is interesting. If the weather is dry and the level of water in the reservoirs is falling, steam production is increased; if the weather is wet and reservoir levels are rising, steam production is cut down. Last year produced extreme conditions in both directions. February was exceptionally cold and dry, with no water coming into the reservoirs, and in that month 40 000 MWh of steam power were generated. October was quite the opposite, being exceptionally wet, and steam production fell to 10 000 MWh per month.

In conclusion, I should like to add a few words to the interesting remarks of the authors about pumped storage. There were pumped-storage plants on the Continent—in the Black Forest, the Ruhr and elsewhere—before the war. I was concerned in 1935–36 with an attempt to promote a 225 MW scheme at Loch Sloy for pumped storage. The site conditions were attractive, with a large low-level reservoir in the shape of Loch Lomond. When the Hydro-Electric Board took up the scheme after the war, however, it proved more economical to bring in water from the neighbouring catchments by tunnels and aqueducts and do without pumps. We are now, however, building part of the Shira scheme in Argyllshire as a reversible scheme with a fairly small installation of 5 MW of pumping capacity.

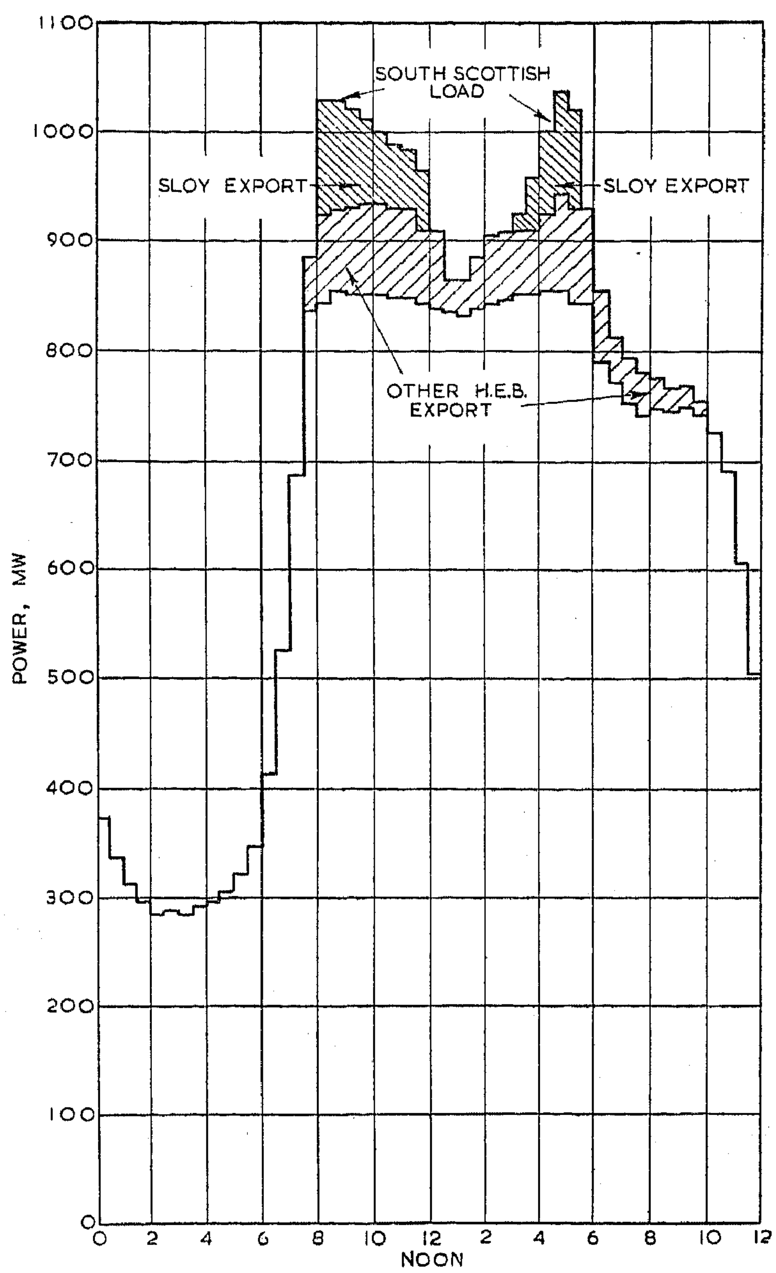

Fig. A.—Typical Hydro-Electric Board export and South Scottish load in December, 1952.

As the authors say, there may be more need in future for pumped storage on a large scale to enable the new large high-temperature high-pressure high-efficiency steam turbines to run at steady base loads, and, of course, any atomic power which may be produced; but the criterion of the success of future pumped-storage schemes is going to be whether the greater fuel economy secured by the steady operation of efficient steam plant will offset the inevitable losses in the pumping and generator cycle of a pumped-storage scheme.

Mr. R. W. Mountain: In Section 1 the authors say, "Hence, changes in the average annual load-factor of a particular project usually mean changes in the installed capacity," while in Section 2.1 they say, "the storage works are not directly dependent upon the installed capacity of the plant." The implication of these two statements taken together appears to be that the cost of storage or the amount of storage is to some extent constant over a wide range of design load-factor for a given catchment area.

Some nine years ago, J. K. Hunter and I tried to generalize,* —I now think wrongly—from an examination of one scheme, and it did appear that the cost of storage is bound to vary rather rapidly in any given catchment area with the design load-factor. I should like to ask the authors, therefore, whether that is so and whether it affects at all the conclusions to which they have come. They may say that part of the answer is to be found in Section 2.5, where there is a reference to the amount of storage, and in Fig. 6, which deals with the relation between firm output as a percentage of mean annual output, and storage as a percentage of mean annual run-off.

In association with the Galloway scheme I should like to pay a rather belated tribute to the genius of the late Colonel McLellan, who foresaw some 25 years ago many of the problems which are discussed in the paper and have been dealt with by the North of Scotland Hydro-Electric Board and others in regard to mixed thermal and hydro-electric schemes.

Would the authors agree that one of the values of peak-load or very-low-load-factor plant is its use essentially as standby plant? The suggestion is that it might be more economical to provide standby plant by this means than by calling on the older thermal plant in other parts of the country.

Mr. F. J. Lane: Figures given in the paper on the cross-Channel cable† indicated that the installed hydro-electric capacity of the British Electricity Authority was about 1% of the total and the energy production about 0·5%. Nevertheless the hydro-electric contribution is greatly valued and any increase would be welcome. The B.E.A. has been anxious to develop hydro-electric power as much as possible, but, as is well known, the problem is not treated on a purely economic basis, and opposition from amenity interests has been almost fanatical south of the Border.

I agree with the authors that the idealized load/duration curve can be misleading. In our normal forward planning, a system is adopted whereby curves of actual demand for typical days covering the four seasons of the year are utilized, and these are applied to the estimated maximum demands for future years, at the same time having regard to plant availability and the restrictions which may occur owing to transmission, inflexibility of plant and so on.

Referring to item (*c*) in Section 2.3.2, and in particular to the statement that it is difficult to restrict a peak-load thermal station to an annual load-factor of less than about 15%, I would remark that the B.E.A. have stations at the present time operating at annual load-factors of 5% or less. By 1965 it is expected that there will be stations operating at even lower annual load-factors. At the same time it will be necessary to cope with the introduction of new thermal plant operating at higher steam pressures and temperatures, so that it will be important to develop the special techniques of low-load-factor operation if maximum economy is to be obtained from the national system.

A pumped-storage project has recently been proposed for North-West Wales. This venture is the first of its kind in this country, and, if legislation permits, first-hand experience will be obtained in the operation of such a scheme in conjunction with thermal plant. The pumped-storage scheme is planned to have a capacity of 300 MW, and it is proposed to connect it into the 275 kV Grid. It will be used in accordance with its position in the national order of merit. During the winter it will run over the three peaks of the day, with maximum pumping at night, but during the summer it will be used only in an emergency and allow its equivalent capacity of thermal plant to go cold, thus saving considerable banking losses. The pumping energy will be provided from spare plant capacity, on the assumption that pumping can cease immediately should the spare capacity be required, and the storage plant could if necessary go over to generation in a very short period of time.

Reference is made to the load factor to be associated with nuclear-energy generation. While it may be ideal that the load factor should be kept as high as possible, conditions in this country and the expected development of the power supplies will lead us into a position where a reduced load factor will have to be accepted. For instance, from some rough figures recently estimated, although we may start with an annual load factor of some 75% on atomic energy plant in 1965 or thereabouts, by 1985 the very much increased quantity of atomic-energy plant—say some 30 000 MW—would be operating at 66·5% load factor, with some 50 000 MW of thermal plant operating at about a 20% load factor. As with the development of the larger thermal units, therefore, techniques will have to be developed for operating atomic-energy plant at lower load factors than the ideal, simply because of the load characteristics of the systems that are being supplied.

Mr. J. K. Hunter: The term "firm power" which is used in the paper requires a little amplification, because there are various degrees of firmness. In a thermal power station, provided that the plant is available and the coal is there to burn, it is true to say that virtually the whole output is firm, but with hydro-electric power the position is different. Estimates of the latter are necessarily based on estimates of run-off, which in their turn depend on the accumulation of past records. As more records are accumulated these estimates become more reliable, but they never become completely reliable and they are never better than approximations to the truth.

For this reason, reservoir storage curves such as that shown in Fig. 6 are inherently related to time. At best they show the degree of firmness of the output expressed in terms of probability. If adequate records are available it is possible to prepare a family of curves showing the percentage of years in which a selected reservoir storage will provide a given firm output; but, however long the records, such estimates are always subject to some uncertainty, and it is impossible to be sure that at some future time river flow conditions will not prove to be more unfavourable than any which have been experienced in the past.

In 1948–49 Europe experienced an unprecedented shortage of precipitation, and this caused considerable embarrassment in countries which depended on hydro-electric power for the bulk of their energy requirements. Over very extensive regions the shortage of run-off was greater than anything which had hitherto been experienced or which had up to that time been anticipated. Again in 1947–48 South-Eastern Canada suffered from an abnormal shortage of precipitation which had the effect of reducing by 45% the output of energy from those stations which were situated on variable-flow rivers. The shortage of water resulted in curtailing the overall output of the Commission's system by 17%—based on the estimated dependable supply. The reduction would have been very much more serious if at that time half of the generating capacity at the disposal of the Ontario Hydro-Electric Power Commission had not been based on continuous sources of supply; i.e. at that time they relied on the Niagara and St. Lawrence rivers for 50% of their energy.

As a result of this experience it was decided to provide thermal backing to the hitherto exclusively hydro-electric system, and between 1950 and 1953 the generating capacity was increased by the construction of two major thermal stations totalling 664 MW, which greatly increased the effectiveness of the hydro-electric stations on those rivers subject to variable flow. During the summer of 1953 the Commission again experienced unfavourable

* HUNTER, J. K., and MOUNTAIN, R. W.: "Hydro-Electric Development—Some Economic Aspects," *Journal of The Institution of Civil Engineers*, 1943, 19, p. 135.

† SAYERS, D. P., LABORDE, M. E., and LANE, F. J.: "The Possibilities of a Cross-Channel Power Link between the British and French Supply Systems," *Proceedings I.E.E.*, Paper No. 1657 S, March, 1954 (101, Part II, p. 284).

flow conditions; indeed the discharge of the Ottawa River was lower than any hitherto recorded, but on this occasion the Commission were able to make good the hydro-electric deficiencies by calling for additional generation from their thermal stations. The Commission have thus amply demonstrated the value of thermal power as a means of making a more effective use of existing hydro-electric installations, and since it is thought probable, on the basis of present load estimates, that by 1962 all the important hydro-electric sources in Southern Ontario will be exhausted, they will be forced more and more to thermal generation or other sources of power.

A somewhat similar position is developing, though more slowly, in Sweden, where recent estimates of load growth suggest that the economically developable water power will be exhausted by about 1970. At the present time, in a year of average run-off, hydro-electric power provides about 95% of the total requirements of the country, but attention is now being given to the desirability of planning future stations to operate at smaller load-factors than have hitherto been customary, in the expectation that one day they will be integrated with thermal stations. Such integration of hydro-electric and thermal power is at present very incomplete, but as it is developed it will result in more efficient use of the country's water-power resources—a considerable part of which now goes over the spillways.

Mr. A. A. Fulton: While it is true that so far as cost is concerned storage works can be regarded as independent of the power tunnels and plant, the storage needed to maintain an evenly distributed flow throughout the year is more than for a plant whose greatest output coincides with the wettest part of the year.

Instead of comparing the incremental cost of a hydro-electric plant with that of a thermal station, it is possible to decide whether to increase the capacity of the former by comparing the rate of increase in annual charges for larger tunnel and plant with the rate at which the all-in unit price of the particular tariff increases with decreasing load-factor. At current costs of tunnel driving, steel pipes and plant, it is advantageous to increase plant capacity to the maximum, because, as shown in Fig. B, the cost curve rises less steeply than does the tariff curve.

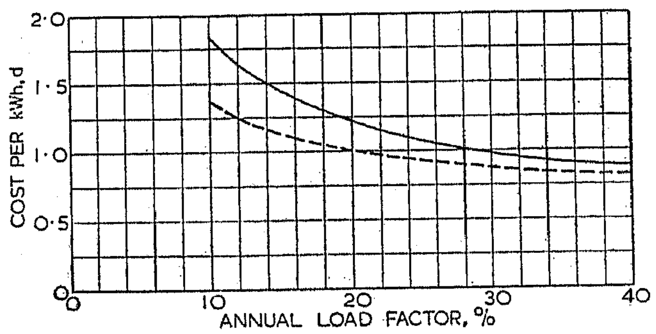

Fig. B.—Variation of cost with annual load factor.
——— Value of energy at Grid tariff (end of 1954).
— — — Cost of generation.

The value of coal saved is now recognized as a justification for expenditure on hydro-electricity; where an expenditure of, say, £40 000 000 results in the saving of 500 000 tons annually, the value of the coal so saved is under £4 per ton. This takes no account of the saving in capital cost of any steam plant rendered unnecessary by the provision of the hydro-electric plant.

The storage curve shown in Fig. 6 interested me particularly. I have compared it with information published in the *Proceedings of The Institution of Civil Engineers*, namely (i) W. J. E. Binnie's curve of 1931; (ii) Fig. 7 in C. M. Roberts's 1951 paper, and (iii) Table 2 of my 1952 paper. Even after adding to mine the 5% which I then recommended, I find that the authors' curve is still about 5% better than mine and fully 10% better than the others. A comparison is shown in Fig. C. Will the authors say how they arrived at their curve?

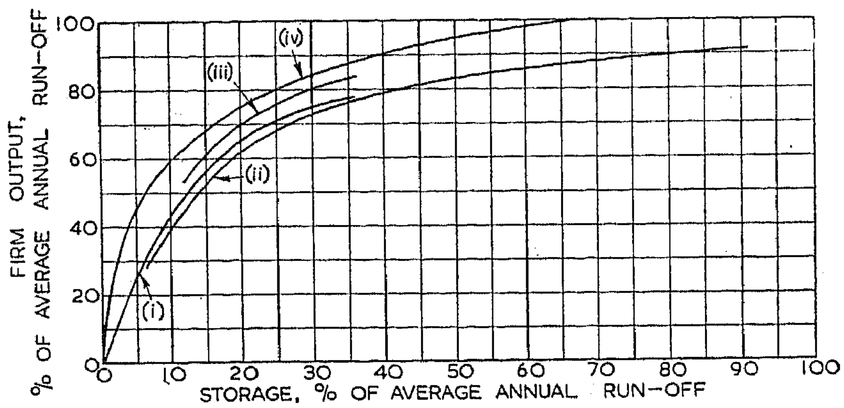

Fig. C.—Comparison of storage curves.
(i) Binnie, 1931.
(ii) Roberts, 1951.
(iii) Fulton, 1952.
(iv) Haldane and Blackstone, 1954.

I agree with Mr. Hunter that in Fig. 6 the term "firm output" needs qualification. Its meaning is slightly different when used to describe the provision of a guaranteed even flow all the year round compared with short-term operation for, say, five days a week and at higher rates during the winter than the summer. Moreover, the evaluation of storage requires some qualification. In practice, it is customary to keep reservoir levels down to catch the odd spate and avoid spill, so the true storage can be some 5–10%, or even more, less than the nominal storage.

The idea of special model turbine tests in replacement of full-scale site tests does not appeal to me: it is only a short step to having no tests at all. The time would soon come when the model test for one plant would be applied to another of different size, but for the same specific speed, with no more bother than an appropriate adjustment of the multiplying formula.

I do not think that there is likely to be any wholesale change-over to the new electronic governor mentioned by the authors. For large plants responsible for system frequency it would be very helpful, but for the remainder the need is rather for a governor which will keep the sets sufficiently close to their allotted share of the load to ease the job of the control engineer while ensuring the most efficient use of available water.

Mr. E. M. Johnson: In Section 6.2 the authors deal with the question of generator size, and state ". . . the problem of increased output is principally one of transport to site and erection." The slow-speed generators to which this remark applies may be built of almost any output but divided for transport to meet the most stringent transport limits imaginable.

The authors also state that, as a result of such machines being taken to site in pieces and then erected at the site for the first time, "certain tests which it is practicable to carry out only in the manufacturers' works cannot be made." I do not agree. Many machines to be erected on site in the way which they describe have, in fact, been erected and tested in the manufacturers' works. That has been particularly the practice in this country. In this class of business, of course, until quite recently all our machines went abroad, and many owners consider that the test of machines in the works has a value in that it gives the operating staff confidence in the machines. It has been quite usual to test one machine out of a number, and the cost of doing that is relatively very slight.

In the same Section of the paper the authors draw attention to the fact that in the speed range of 400–600 r.p.m. the attainable generator output is well above what is at present required. A challenge comes to the generator manufacturer in the next higher speed range, 750–1 000 r.p.m. I should like to comment on a dangerous practice that is met with here and there, of

attempting to raise the upper limit of attainable output of a 750–1 000 r.p.m. generator by allowing the measured first critical speed to be below the runaway speed. There is no true parallel between a water-turbine-driven machine and a steam-turbine-driven machine, because when a water-wheel runs away it is power drive and may linger at the first critical speed where there may be resonance leading to serious damage. A much better way of dealing with the problem is one which is being pursued by turbine makers, and consists in artificially reducing the maximum speed for which machines have to be designed.

It is unfortunate that the authors have chosen as a basis for Fig. 7 the phenomenal rise of prices during the last half century. This was greater than in the previous 300 years, and I think a much smaller rate of increase would have been more realistic.

In Table 3, scheme (*a*) includes about 45% greater reservoir working capacity than scheme (*b*), yet the capital cost is affected to the extent of only about 2%. If these figures are correct it would seem that the cost of reservoir working capacity has little effect on the total cost. Does this not have an important effect on the conclusions to be drawn?

Mr. C. W. Marshall: My long experience of hydro-electric developments in Scotland leads me to draw attention to the fact that early economic studies usually resulted in deferment of construction, with consequent increases in capital cost and loss of irreplaceable fuels. A noteworthy exception to this rule is the Galloway scheme, which was constructed at an opportune time and has been a conspicuous success.

Regarding the present electricity supply situation in South Scotland, it is useful to note that about 30% of the total power requirements were derived from hydro-electric sources, about two-thirds of which came from the North of Scotland system. It was frequently possible to provide all the night load requirements by hydro-electricity alone, although for security we operated a few of the most economical steam sets to safeguard the industrial areas.

A minor point of practical interest to operating engineers is that when the highly efficient modern steam sets in Glasgow were shut down for several hours during the night, the noise emission was of the order of 100 phons. This caused serious disturbance to the would-be sleepers for a wide area round the station. The noise trouble was, however, completely eliminated by application of an extremely efficient spray silencer devised by the superintendent of Braehead power station. It is also important to realize that the sporadic starting and stopping of steam plant is expensive in fuel and plant maintenance.

Hydro-electric plant is almost completely free from these disadvantages, and I should like to record a tribute to the designers and constructors of the Galloway scheme, which has now traversed almost every weather condition that has been encountered in the area. I especially wish to associate that tribute with the names of William McLellan and James Williamson.

There is only one respect in which a slight improvement could be effected, so far as my experience shows: the rates of rainfall and of run-off from the hillsides into the reservoirs can be phenomenally high, with the result that the siphon reliefs may come into action; and as these cannot be stopped until the water level has fallen sufficiently, flooding may result. It should be possible for the authors, who are familiar with balanced systems of protection, to devise a hydraulic analogue of the Merz–Price system which would set this to rights.

On the general question of hydro-electric machine design, I find it difficult to accept the authors' contention that the theoretical basis is as unsatisfactory as they have indicated. I feel sure that the water-turbine designers and manufacturers have a firm basis from which to work, otherwise they could not have achieved the remarkable success which they have obtained.

The subject of testing hydro-electric machines has always been controversial, and I have so far been unable to obtain a code of testing practice for which our research advisers will vouch. I attach great importance to this matter, for although I agree with Mr. Lawrie as to the showroom value of Scottish hydro stations, I suggest that they could be of much greater value as hydro-electric research centres. The Galloway stations are particularly convenient in this respect, and measurements made on the plant there could be more convincing to potential customers than any laboratory-scale tests.

Mr. H. Headland: Oversea, remote water-power projects and lack of fuel resources often go together, whereas in Britain the cost of thermal generation is the criterion. The theme is therefore the economic hydro-electric/thermal plant ratio for different conditions.

Although the authors define firm annual load factor in terms of the driest year, requirements may be modified by analysis of drought frequency and duration or on a probability basis, since supply reliability in underdeveloped areas need not initially approach that demanded in industrial countries.

The points concerning optimum installed capacity might be illustrated by developments in Scotland, where initial schemes were designed for low load-factors with subsequent stations for higher load-factors, in contrast with which we find Owen Falls and Kariba being developed for load factors of 60–70% and joint thermal and hydro-electric schemes in the Middle East because of river flow characteristics.

In Britain, power demand follows seasonal run-off, but in Switzerland, where run-off depends on snow melt, there is a standardized procedure which gives seasonal values for energy. It might be worth considering whether this concept is applicable in Britain.

There are few statistics concerning hydro-electric plant availability, but on one large system 98–100% is common and values below 95% are unusual. An American I.E.E. committee has given a figure of 0·46% of the exposed time for forced outages.

The suitability of hydro-electric plant for fluctuating loads may depend on the surge chamber being capable of absorbing severe load increases. System characteristics may change during the life of a station, and a tendency to reduce surge-chamber dimensions requires investigations to define design conditions more closely than seems possible at present.

Dr. J. H. Walker: The paper emphasizes the increased capital cost of hydro-electric stations as compared to steam stations. In this connection some reduction in the cost of machines for the former could be obtained by eliminating acceptance tests in the factory. The practice of carrying out acceptance tests on site is widespread in the United States and Canada; in addition to being covered by an appropriate test code, it is normally included in specifications issued by American operating companies and consulting engineers. This not only reduces costs but also shortens delivery times and releases valuable factory space. The disadvantage, of course, is that testing in the factory can be carried out with greater accuracy, and in addition the designer is denied the opportunity for experimental tests required for development work.

On the question of turbines, the authors' opinion would be interesting on the use of the propeller type, which is very similar to the Kaplan but much cheaper, with fixed blades and substantially the same full-load efficiency. It is applied to a large extent in America in hydro-electric stations having a total output of several hundred megawatts, so that the efficiency of the station is maintained by keeping all running sets on full load and shutting the sets down as the load on the station falls.

It would be of considerable interest to engineers in this country if the authors could give their views on the extent to which the power from the Severn barrage, when built, could be co-ordinated with the cross-Channel power link with France.

Mr. D. J. Bolton: In Section 11, referring to the pumped-storage scheme, the authors state that every kilowatt-hour generated represents a definite financial loss. Perhaps we can apply that phrase to any storage scheme by saying that every kilowatt-hour provided for by way of storage represents a definite financial loss; in other words that the cost of impounding —so far as it is a kilowatt-hour cost—is broadly more than the fuel and other running costs of a steam station. On the other hand, as the authors point out in Section 2.1, the kilowatt cost of a hydro-electric scheme, or the incremental cost of increasing the plant capacity, is generally less than with a thermal station. Putting those two together, we get the equation that the lower the design load-factor (other things being equal), the more economic is the scheme likely to be, so that it is just a question of what is the lowest load-factor which can be accepted; in other words, what is the minimum number of kilowatt-hours to be associated with a kilowatt in order to give it the proud title of a firm kilowatt?

In estimating this I am not sure whether the authors have given sufficient credit to hydro-electric plant for its operational elasticity. A curve similar to that in Fig. 2 was given by Cooper as Fig. 10 in his paper on load dispatching.* It shows a load/duration curve, and side-by-side are rectangles showing the difference between the ideal and the actual. The rectangles at the bottom show the deficiency of kilowatt-hours as compared with the ideal, and the rectangles at the top the excess of kilowatt-hours which had to be generated by low-merit plant. Any station or system engineer, with that curve in mind, if he were offered a peak-load steam station with only enough coal for 200 hours a year, would say that it was little use; but if he had a hydro-electric station with only enough water for 200–300 hours a year, would he necessarily make the same reply?

Mr. Cooper attributed the divergence at the top of the curve almost entirely to the lack of operational flexibility, such as unsuitability for 2-shift working, quick starting and stopping, and to extensive running of low-merit plant to provide security of supply. I suggest that the position may be different with hydro-electric plant. In Mr. Cooper's and the present authors' curves the top 10% of the load lasted for $1\frac{1}{2}$–2% of the time. If we apply that to our present peak of 16 000 MW and hold to the ideal curve, we shall have about 1 600 MW of plant with a load-factor of about $1\frac{1}{2}$%, i.e. about three times as much as the whole of the hydro-electric plant in this country, including the North of Scotland. I do not suggest that we could keep to the ideal curve, but it suggests that, if we have a load in the country of the order of 1 600 MW persisting for only 150 hours a year, it provides us, with our present interconnected schemes, with the elbow-room to fit in some very low load-factor hydro-electric or pumped storage schemes.

The difference between the ideal and the actual operating times is worked out in Figs. 2–5, and I have two criticisms to make of the method. The first is that it seems to be based entirely on typical steam conditions. The difference between the straight lines A–A, etc., in Fig. 4 and the curved lines arises because on many days it was necessary to have sets steaming and not necessarily running, in order to provide security. A hydro-electric station might have served the same purpose on many of these days without using a gallon of water.

The other objection to the method is its purely empirical basis. The authors suggest that the same percentage of any peak should always be supplied by the hydro-electric plant. If the peak of the year is taken as 100 units and the hydro-electric plant supplies 1%, it supplies 1 unit, and if on some other day the peak is 70 the authors suggest that the hydro-electric plant should provide 0·7 unit. I wonder why? There is then a margin of steam plant; why call on the hydro-electric plant? The fact that the latter is there ready to come on means that it is in quite a different position from the steam plant with which it has been compared.

Mr. K. H. Tuson: I endorse the requests for more information on Fig. 6, and suggest that the authors might give the form of the annual load curve on which this figure is based. I should also like them to set out the model formulae which are represented by the dots A–F in Fig. 8.

Turning to Section 4, I think that the first characteristic which the authors give of nuclear energy, namely that power plants must be at a very long distance from centres of civilization, is a purely passing disadvantage and that the dangers are much exaggerated in the public mind. A reactor at Chalk River broke down or exploded without any very disastrous results, although the outage was of extremely long duration. I do not think that it is fair in computations to load nuclear energy with the cost of unduly long transmission lines.

The figure of 1d. per kilowatt-hour for the cost of nuclear energy has been mentioned several times and is referred to in the paper. Have the authors any information on the make-up of this figure? My belief is that it does not give sufficient weight to the cost of the fuel (because it comes from Government establishments), to the cost of processing and ash disposal and, in the case of breeder reactors, to the cost of extracting the plutonium. Until some authority publishes a reasonably detailed estimate, little weight can be given to the *ex cathedra* pronouncements of overall figures.

Mr. V. G. Newman: The principles set out by the authors for the integration of hydro-electric with thermal generating plant are broadly in line with those followed by the B.E.A. The characteristics of suitable hydro-electric sites in the Authority's area are such that development can most profitably be carried out for peak-load generation at annual load-factors of the order of 10–20%, and an economic comparison with alternative coal-fired plant must take into account the much higher load-factor at which the latter would operate during most of its life.

The improvement in average system efficiency which results from the addition of new thermal plant, which is sacrificed when capital is allocated instead to hydro-electric construction, is greatest during the first year of operation, when the new station is one of the most efficient on the system and operating at its maximum load-factor. Consequently, if it can be shown that the hydro-electric scheme will be financially attractive during its first year of operation, its economic soundness throughout its life will be established.

A careful study of the full effects of a pumped-storage scheme on the operation of the system will often show that the fuel saved as a result of the displacement of thermal plant, which would otherwise have to be reserved for peak-load and standby duties, more than offsets the additional fuel consumed in supplying the pumping energy. Moreover, with gradual improvement in system efficiency, the pumped-storage scheme will require less coal year by year.

The authors do not appear to have taken into account in their estimates for a pumped-storage scheme items (*b*), (*c*) and (*d*) referred to in Section 2.3.2. From calculations recently made by the B.E.A. it would appear that, for the size of installation considered in the paper, these three items would entail a net reduction of some £50 000 in the estimated annual surplus.

Mr. Lane has already mentioned briefly the pumped-storage scheme which the B.E.A. is at present seeking parliamentary

* COOPER, A. R.: "Load Dispatching and the Reasons for it, with special reference to the British Grid System," *Journal I.E.E.*, 1948, 95, Part II, p. 713.

powers to construct, and a few additional figures may be of interest. The operating head will be 1 000 ft and the total installed capacity 300 MW. Operation will be on a 5-day pumping cycle with generation over 4 hours a day. The daily load-factor will be about 16·7% and the annual load-factor about 11·4%.

A further project, a hydro-electric scheme, is also proposed. This is the Rheidol scheme in Cardiganshire, which will develop an output of 49 MW in two main stages, having an aggregate head of 900 ft. The average annual load-factor is estimated at 19%, and the storage capacity will correspond to some 21% of the average annual output. This will ensure that the installed capacity will be wholly firm, even in a dry year, although the energy output in such a year will fall to about 75% of the average. This is in very close agreement with Fig. 6 of the paper.

Dr. T. P. O'Sullivan: I should like to refer to two points in the paper which are largely complementary. The first is in Section 5, where the estimated life of a hydro-electric station is given as approximately 60 years, and the second is in Section 2.1, where the available energy is stated to be fixed by run-off, as it very largely is. In that connection, however, I should like the authors' opinion on the possibilities of certain adverse factors affecting the available energy.

The first—perhaps the least important, although it applies quite forcibly in tropical countries—is evaporation, and the second is silting. In one instance with which I am familiar there is a relatively small reservoir involved with a dam of low head, and the evaporation is some 20% of the total capacity of the reservoir; this is in Northern Nigeria, where the dry season lasts for at least six months of the year. The maximum temperature there is approximately 105°F, but I understand that in certain other parts of the world, including areas of the United States, the Sudan and the Middle East, evaporation takes place at an even higher rate.

So far as I can gather, silting is not a great problem in this country, neither does it seem to have caused undue anxiety in Europe, South Africa and India; however, there have been some particularly troublesome cases in the United States. The Zuni reservoir in New Mexico, of 14 800 acre-ft, lost 20% of its capacity five years after completion, 35% in ten years and 63% in 15 years. At the end of 15 years it was decided that special measures should be taken in the form of silt traps and revetments to slow down the rate of loss, after which it was necessary to go further and put in an extensive sluicing system to set up erosion in the bed. It is claimed that, during a drought in 1941, a group of power operators in the Southern States of America lost 90 000 MWh through silting.

I should like the authors' comments on these factors, which may become of some considerable importance in connection with works in certain oversea locations.

Mr. S. C. Brealey (*communicated*): I have just been engaged in examining a project which includes thermal generation at an open-cast lignite mine site oversea and integration of the station into a predominantly hydro-electric system. In this case it is obvious that the economic comparison must be drawn between a hydro-electric station on the one hand and a combined mine and power station on the other. The generation cost in each case consists solely of labour, stores, depreciation and other capital charges. In the thermal scheme, fuel is an internal transaction only. The capital cost of the combined mine and power station is comparable with that of new hydro-electric schemes. In this case, therefore, on the same basis as Fig. 7 and allocating 60 years' life to the initial development cost of the mine, the additional benefit which the owner could obtain by installing a hydro-electric station is very considerably less than the authors indicate. Furthermore, no additional benefit at all would accrue until 30 years had passed, and it is doubtful whether it would then be sufficient to influence materially a choice made at the present time. The additional benefit to the owner according to the authors is the shaded area in Fig. D (i), while according to the above it is as shown in Fig. D (ii).

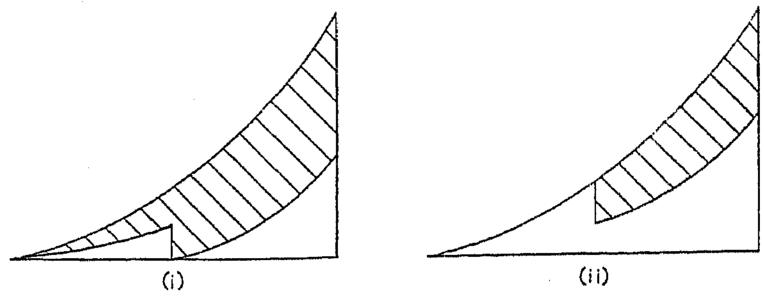

Fig. D.—Benefit to owner due to rising prices. Shaded areas show additional benefit due to hydro-electric generation.

(i) Mine neglected.
(ii) Mine included.

It may be argued that this would not affect a purely electrical undertaking, which would not usually own its own mines, but, of course, the depreciation and other capital charges on the mine are included in the price of fuel. Where fuel is obtained from a number of mines and where the price structure is unified, these effects are masked, but they are nevertheless still present. During the first 30 years such a thermal power station would benefit by the lower capital charges on mines constructed before the commissioning date (as would all other fuel users), and during the second 30 years the reverse would be true (assuming an average of 60 years' life for all the mines involved in the fuel price structure).

The point is that, when comparing the economics of hydro-electric and thermal generation (as distinct from stations), the economics of the mine should not be left out, and this is particularly true in countries where public control of the mines and power stations demands consideration of the wider economic ramifications. In this country, under present conditions of coal scarcity and restrictions on capital expenditure, the mine must be considered with the power station when it is remembered that a 1 000 MW station at 50% load factor consumes coal at the rate of about 5 000 tons per day; this is the output of a large colliery, and therefore a colliery must be sunk somewhere to supply that station.

A further point which operates against the case for hydro-electric stations is the fact that an installed kilowatt capacity of hydro-electric plant is very often not as valuable as an installed kilowatt capacity of thermal plant, because the latter is more firm.

A number of speakers emphasize the saving of coal which hydro-electric stations bring about, for instance in Scotland, but in some cases it can be the other way round with thermal stations bringing about a saving in water. This is often the case where generation is secondary to the demands of irrigation and where rainfall is irregular. In these cases the ratio of firm to total capacity is very low and may even be zero, and the value of an installed kilowatt capacity is correspondingly reduced.

One must therefore conclude, from these considerations and from the authors' admission that many factors have been omitted, that the conclusions in Section 5 have little value. This is not a plea for more thermal stations, but a plea for treating each system on its own merits without oversimplified generalizations. If one can generalize at all it can be said that hydro-electric generation has the advantage over thermal generation in reduced labour and stores costs at the expense of reduced firmness.

[The authors' reply to the above discussion will be found on page 330.]

NORTH-WESTERN SUPPLY GROUP AT MANCHESTER, 8TH FEBRUARY, 1955

Mr. E. M. Johnson: In the very early days of electricity supply the view was sometimes held that there was no future for electricity until means could be found of storing it. Fortunately, the handicap has not proved as serious as was thought. The reason for this has been the comparative abundance of the prime sources of energy. Nevertheless, there is some truth in the old view; rising costs and increasing scarcity of sources of energy will give added point to it.

The authors deal with their subject in general terms, and I think it is unfortunate that the title of the paper and a part of the presentation of it give an impression of a much more restricted review of the subject than that which the authors in fact present. The principles of the method of approach which they elaborate are applicable to any mixed power system, whether having pumped storage or not. The latter is merely a special and very important example of a possible component of a mixed system.

That the operation of mixed systems provides advantages not available from one alone is, of course, not new. So far as I am aware, however, the paper is the first published analysis of the basis governing the development of such systems. A very early example was the interlinking of power systems having low-head plants with others operating at high heads, which took place in Switzerland immediately after the 1914–18 War. The addition of pumped storage was being discussed even in those days.

The authors, of course, go much further and include even the "installation of thermal plant especially for firming the water power." I think, therefore, that they may well claim to have dealt, not only with the analysis of all the factors governing the economics of mixed power systems (of whatever sort), but also to have issued a kind of challenge to power-system operators to endow their systems with precisely the characteristics they require by mixing the types of generating plant and, if advantageous, by adding pumped water storage even at low efficiency.

Mr. H. Headland: Section 2.3.2 is an admirable summary of the effect of hydro-electric plant on overall fuel consumption. This problem also occurs in a different form for tidal-power plants with or without pumped storage. The difficulty is to forecast future trends of the factors concerned, and similarly the question of increasing plant capacity requires determination of the expenditure which can be justified to cope with future conditions, especially where tunnels, surge chambers and pipelines are involved. These points emphasize the element of judgment entering into hydro-electric station design, but nevertheless it should be feasible to devise approximate economic criteria to take the appropriate factors into account. The authors might also have mentioned that it is sometimes economical to increase the plant load-factor by diversion of adjacent catchments to meet the needs of an expanding system.

It is perhaps fair to mention that several studies of firming with pumping plant suggest that money can be better invested in increased storage, even though the economic height of the dam might appear to have been reached. Short-term weather prediction is now an established facility in hydro-electric system operation, and much research is being devoted to the long-term aspect. With the former it would seem that better use might be made of firming by pumping by allowing greater latitude in operation of storage capacity, particularly if there is some diversity of run-off in several catchment areas.

The authors are to be commended for an authoritative statement on the effect of nuclear power in relation to hydro-electric development. This should dispel much loose thinking on this question by those unfamiliar with both sources of power.

The novel, but admittedly oversimplified, treatment of the rising-price problem reinforces the need for a long-term view of marginal projects such as the Severn Barrage, and a more realistic economic criterion than that used in the 1945 Report when coupled with rising coal costs and other factors which have changed in the meantime.

It is unfortunate that no reference is made to outdoor, semi-outdoor and underground stations or to new arrangements of turbines and alternators, including machines where the conventional spiral casing and draft tube have been simplified, with the alternator housed in a submerged chamber. Such developments have resulted from the need to economize in space and expenditure, and are perhaps more important than the details to which some attention has been devoted.

The statement in the penultimate paragraph of Section 8 should not be accepted by plant designers with complacency. In low-head and tidal-power schemes, civil-engineering and plant costs may be about equal. The fixed annual charges on the former are about 3·74% against 4·68% on the latter, and reduced plant costs, perhaps bringing cheaper civil-engineering works in their train, are worth seeking on economic grounds.

The paper encourages the application of reversible Francis pump turbines, but passes over the operating head without comment. It is claimed in the United States that these can be designed for heads exceeding 1 000ft, and while this is hopeful, no experience is available to provide convincing evidence that a single turbine runner can be used where experienced pump designers would undoubtedly employ 2-stage impellers.

The reference to the quality of steel castings should have the unqualified attention of steel founders in this country, where it is apparent that the casting technique for runner and other components for hydraulic machines has not received the attention which it deserves. On the whole, welded construction has proved satisfactory, but among hydraulic engineers and steel founders there is a need for acceptance of radiographic and other non-destructive methods of testing as a routine rather than as a procedure to be adopted when trouble is discovered.

While there are undoubted merits in testing model turbines, they will not have universal acceptance until prototype/model similitude can be assured and scale effects for partial loads are resolved. Current empirical or semi-empirical formulae predict peak efficiency, but a recent approach by Hutton* covering full and partial load performances of Kaplan turbines merits the attention of those who have model and prototype test data to check it.

The inter-territorial character of interconnected transmission might also have been associated with difficult problems arising in Europe, Africa, America and Canada, where water-power development on rivers affecting sovereign States have had, and will have, to be solved.

Mr. E. W. Connon: Twenty-five years ago it was generally considered that hydro-electric stations, because of their high capital cost, had to work at a high load-factor, and the paper demonstrates how, as a result of the appreciation that the capital cost is generally related more to the energy than to the power, the trend has been reversed. To-day, the quick-starting characteristics of hydro-electric plant, enabling the stations to be used to assist at times of rapid load rise and of unexpected plant shortages, are those which are perhaps most valuable in the operation of interconnected systems. The pumped-storage scheme is a logical outcome of these requirements.

When discussing the relative merits of 2- and 3-machine installations for pumped storage, the authors do not appear to mention the problem of starting, which would seem to increase

* Hutton, S. P.: "Component Losses in Kaplan Turbines and the Prediction of Efficiency from Model Tests," *Proceedings of The Institution of Mechanical Engineers*, 1954, 168, p. 743.

considerably the electrical costs of the 2-machine installation, since hydraulic starting cannot be used. Can they say what methods are proposed, and what they will cost?

(Communicated): It seems to me that a simpler way of considering the rising-price phenomenon is to say that the rate of interest is, in reality, reduced by the price increase if the real value, in goods and services, is considered. Anyone who has compared the purchasing power to-day of a Savings Certificate bought, say, in 1939 with that of the cash with which it was bought will appreciate this.

Mr. J. F. Dunn: With regard to the welding of pressure parts, it is in my experience noteworthy that many Continental manufacturers adopt a 100% radiographic control technique—which means that every inch of important welding runs is photographed. These records are carefully examined by persons qualified in this respect, and any defects which are revealed and which are judged to be below a certain very high acceptance standard are cut out and repaired. The records are then stored for possible future reference. This very thorough non-destructive testing procedure is emphatically stated by every manufacturer who practises it to pay high dividends, and there is no doubt also that it has a profound psychological effect upon visiting inspecting engineers.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. T. G. N. Haldane and **P. L. Blackstone** (*in reply*): We are glad to have Mr. Lawrie's support on a number of matters covered in the paper. All who have been concerned with hydro-electric work will agree that the progress which has been, and is being, made in the North of Scotland is of immense benefit in helping to promote British hydro-electric work oversea.

In answer to Mr. Mountain, we consider that under normal circumstances the amount of storage required, and hence its cost, is affected only slightly by the design load factor. We agree that hydro-electric plant is certainly more suitable for standby purposes than thermal plant, bearing in mind the coal consumption which must continue when thermal plant is kept available but not generating. This is particularly true of pumped-storage plant, and it may well be that, if such plant is used largely for standby purposes, the annual consumption of pumping energy will be less than usually shown in calculations, such as in Table 3.

The expression "firm power" does require some amplification, as Messrs. Hunter and Fulton suggest, and a working definition might be that hydro-electric power can be regarded as firm if it is capable of development in the worst conditions which can arise in 30 years; but, of course, still worse conditions may occur over some longer period. There must always be some margin to deal with the completely abnormal year, or alternatively, readiness to accept some restriction under very rare circumstances. No system can ever have 100% reliability, and in some countries such may not be necessary. How much additional expenditure is justified in approaching closer to 100% reliability must be a matter of judgment. An all-thermal system may not be completely reliable, owing to possible restrictions in the supply of fuel due to weather and other causes. We therefore see no reason to agree with Mr. Brealey that a hydro-electric kilowatt is necessarily less valuable than a thermal kilowatt on grounds of reliability.

Mr. Lane says that some B.E.A. stations operate at annual load-factors of 5% or less. We wonder whether the explanation may not be that such very low load-factors occur when thermal plant is used largely for standby purposes. It may be that there are not many thermal stations in regular, as opposed to standby, use which have load factors much less than 15%.

Mr. Lane also refers to the load factor of future nuclear plant. To avoid running such plant at reduced load-factors, which would be uneconomic and technically difficult, we visualize the possibility of nuclear plant operating in conjunction with pumped-storage plants, so as to maintain the load factor on the former as high as possible.

As both Mr. Lawrie and Mr. Fulton point out, there is a concealed benefit accruing from expenditure on hydro-electric plant because of the saving of coal. We feel this can best be regarded as due to the difference between the home prices of coal and the higher price of imported coal. It must, however, be borne in mind that some saving of coal may result from expenditure of the same capital on new thermal plant instead of the alternative hydro-electric plant.

Mr. Fulton has made the interesting point that the justifiable installed capacity of a hydro-electric station can be related to the rate at which the all-in kilowatt-hour price of the B.E.A. Grid tariff increases with decreasing load-factor. For practical purposes in this country, such a criterion would be very suitable provided it can be assumed that the Grid tariff accurately reflects the true costs of generation. But, of course, it still remains necessary to show that the low-load-factor hydro-electric plant can be fitted satisfactorily into the adjusted load/duration curve.

Fig. 6 has been commented on by Messrs. Fulton, Hunter and Tuson. It is one of many such curves which can be drawn from a study of mass run-off curves for different catchments. Its shape will vary according to the ratio of maximum to mean monthly demand assumed. The curve shown is an average for several different catchments in Scotland, and was intended rather to illustrate the principle of firming of power by pumping than to be taken quantitatively. We wonder whether Mr. Fulton's curve (iii) in Fig. C perhaps applies to one particular catchment.

In reply to Mr. Tuson, the estimated cost of nuclear power of 1d./kWh was taken from statements published before the issue of the Government's White Paper, which (taking account of the probable value of the plutonium by-product) assumes 0·6d./kWh. While experience of the accident at Chalk River was reassuring, it is probable that reactors less inherently safe than those at present being built will eventually become the most economic, and that it will be considered necessary to site such reactors in fairly remote areas.

We agree with Dr. Walker that propeller turbines still have their uses, provided that the relatively high drop in efficiency at loads above and below the optimum can be justified by saving in initial cost. This will more easily be done in large multi-unit stations running on base load.

In answer to questions raised by Messrs. Fulton and Marshall, the criterion for model-turbine or site-efficiency tests is: Which will give the more accurate and comprehensive results consistent with reasonable expenditure, time and inconvenience during testing? It seems that, if the answer to this is in favour of homologous model tests, there is no justification for prejudice on the grounds that the actual prototype machines are not tested for efficiency. Certain tests can be made on models which are impracticable on site.

A new British Standard for testing water turbines is now being prepared. It is hoped to carry out some research into different methods of flow measurement at one of the North of Scotland Hydro-Electric Board's stations.

While we cannot wholly follow Mr. Bolton's line of argument in which fixed storage costs are compared with steam running costs, we largely agree his conclusion. In regard to the empirical

method illustrated by Fig. 4, it must be borne in mind that at other than peak times there may not be surplus steam plant available because of outages for maintenance.

We agree with Mr. Newman that the factors enumerated in Section 2.3.2 have to be considered in deciding whether or not to proceed with a pumped-storage scheme. As pointed out in Section 3, however, it is likely to be found that over a long period the total of the effects is zero.

We also agree with Dr. O'Sullivan as to the importance of both evaporation and silting in certain circumstances. In extreme conditions silting might affect the assumed life of the works for sinking-fund purposes.

Mr. Johnson suggests, in connection with Fig. 7, that the rise in prices during the last half-century is phenomenal. This must be a matter of opinion, of course, but there is no doubt that the fall in the value of money is still continuing; and whatever may be the rate during the next half-century, the effect illustrated by Fig. 7 is likely to be important.

The pumped-storage scheme, particulars of which are detailed in Table 3, is based on an actual project recently investigated. We agree with Mr. Johnson that in this particular case the extra cost of increasing storage capacity was, owing to the nature of the ground, unusually low.

Mr. Brealey raises a complex problem by taking into account capital expenditure on coal mines. We do not think this is relevant to Fig. 7, which relates simply to the normal capital expenditure incurred by the owners of hydro-electric and steam stations respectively. We have been careful to point out that financial gain accruing to the owners of power stations due to fall in the value of money is not necessarily gain to the nation. Nevertheless, the effects dealt with in Section 5 are of considerable importance, particularly to those financially responsible for expenditure on hydro-electric works.

With Mr. Headland's remarks we are much in agreement, especially in his emphasis on the element of judgment entering into hydro-electric station design.

We are not in a position to deal here with the problem of starting of pumping plant raised by Mr. Connon, but we agree with his comment on the purchasing power of savings certificates, and with Mr. Dunn's remarks on radiographic control of welding.

We regret that lack of space does not permit us to reply to all of the many interesting points which have been raised.

DISCUSSION ON

"SERVICE EXPERIENCE OF THE EFFECT OF CORROSION ON STEEL-CORED-ALUMINIUM OVERHEAD-LINE CONDUCTORS"*

NORTH-WESTERN SUPPLY GROUP AT MANCHESTER, 19TH FEBRUARY, 1954

Mr. P. McKenna: I am glad that the authors have mentioned the effect of humidity, since most forms of corrosion, particularly electrolytic types, depend on the presence of moisture for the completion of the electrolytic cell. I have had some experience of corrosion on transmission lines in Egypt, where it was very noticeable that in the Higher Nile area, where the atmosphere is extremely dry, corrosion was non-existent, but in the Lower Nile area, where the percentage humidity is extremely high, severe corrosion occurred around industrial areas, even though these were isolated, owing to the humidity trapping the corrosive elements on the materials. It is significant that corrosion was confined to the higher portion of transmission-line supports.

Of the two broad classifications into which the authors have divided the problem, the case of corrosion due to saline deposits is more general, since it can apply to any part of the world; the authors have mentioned the use of plastics, and manufacturers are developing possible solutions other than the application of grease advocated in the paper. These developments are generally on three lines: the application of an aluminium sheath to the outside of the conductor; the application of a sheath to the steel core before the stranding of the aluminium wires; and the application of a new type of plastic with good mechanical characteristics and high resistance to abrasion.

In conclusion I should like to mention that the question of anodizing has been investigated, but unfortunately, without a very high expenditure for special plant, it is impossible to anodize long lengths of large-diameter wire, and it is necessary to have a very high surface finish on the material before the anodizing process.

Mr. T. R. Y. Grahame: In Section 4.1.1 it is concluded that line voltages had effect on corrosion due to attraction of particles of carbon, etc. Can it not also be possible that corona has some effect, owing to the production of ozone and increased oxidization of the strands? This could be borne out by the fact that the larger bodies of joints and anchors are very little affected. Since on energized conductors there will probably exist inter-strand voltages, these again may have some bearing on the rate of corrosion.

It is well known that certain chemicals react with metals to form a protective coating which resists any further corrosion, i.e. fluorine on copper. Has this chemical angle of approach been considered in any detail?

In view of the difficulties experienced with the running of greased conductor, has consideration been given to the use of enamels with a tough, non-cracking characteristic, in particular to the use of silicone enamels or silicone grease?

On the St. Helens–Lockfields line (one of the first to be rewired with protected conductor) grease (*a*) was used with apparent success, and not a great deal of trouble was experienced with the running and jointing of conductors. One or two cases of the slipping of automatic clamps was experienced, but this was overcome by the use of emery cloth in the jaws of the clamp. One case was noted of slipping between the inner and outer strands, resulting in strand breakages.

The stringing of conductors treated with grease (*b*) is much more awkward and has given trouble in North Wales. Many cases of broken strands were encountered, owing to lack of friction between the inner and outer stranding and also slipping of the automatic clamp itself on the conductor. This latter fault can generally be counteracted by stringent cleaning of the conductor with petrol.

The running of conductor when treated with grease (*b*) is

* FORREST, J. S., and WARD, J. M.: Paper No. 1611 S, January, 1954 (see 101, Part II, p 271).

also greatly hampered, since with normal conductor six conductors can be run out at one time, but with the greased conductor only two can be run, thus taking at least three times as long. In addition, the pulleys on the blocks become heavily choked with grease, so preventing smooth running. Further tractive effort causes the conductor to snatch, and in many cases this results in the pulling of the drums off the jacks.

Streamers of grease were not specially noted in this case, but it would appear that this could be overcome by pulling the conductor through a cone as it is drawn off the drum.

Mr. T. A. Smith: It has been said that conductors appear to corrode appreciably faster than large aluminium surfaces, such as roofs. The authors hold this to be due mainly to retention of moisture between the strands of the conductors and to the electrostatic effect of voltage in attracting solid particles. While not disputing the two causes put forward, I think that the configuration of the stranded surface, presenting a ridged appearance, would more readily invite erosion from wind and weather. The flattened appearance of the exposed surfaces of outer aluminium strands on long-service conductors would seem to indicate the action of erosion.

There seems to be a variety of recommended greases. Does a particular grease best counteract a certain type of pollution, or are there a number of greases which are equally effective for all conditions?

On the question of deterioration of conductors, have any cases occurred in this country of conductors which have broken as a direct result of deterioration? The ultimate tensile strength of the 37/·110 conductor is 17 720lb, 40% of which is borne by the aluminium strands. With stringing tensions of the order of 3 500lb, breakage of corroded conductors would appear to be most improbable unless there is considerable deterioration of the steel core.

The first line in the North Western Division to be seriously affected by corrosion was the Hillhouse–Fleetwood line, erected in 1932 in a coastal area. About 3 miles of conductor were renewed in 1948 and 1949.

Other lines then required attention and 4·5 miles of conductor were renewed in 1950, 21 miles in 1951, 23 miles in 1952, and 34 miles in 1953.

This length of conductor is roughly 7% of the total installed in the Division. The majority of the lines affected are located either in coastal or tidal areas or positions subject to industrial pollution. The Kearsley–Rawtenstall line, however, is affected on Holcombe Hill, which is high moorland. The district is some miles from industry, but it is likely that salt deposits are carried by high winds from the sea some 32 miles away. This possibility is perhaps borne out by the complaint of Manchester housewives, when windows, 37 miles from the sea, are spattered with salt in heavy westerly gales.

Since no line in the Division is more than 45 miles from the sea, the effect of sea spray may be the reason why only two or three lines in the Division are unaffected by corrosion.

The line worst affected is the Southport–Penwortham line, closely followed by the Ribble–Wigan line, both of which were erected in 1932. By the end of 1954 it is expected that the conductors on these two lines will have been completely renewed.

Mr. K. Speke: In Section 5.2.2 it is mentioned that a reduction in strength of the aluminium strands to between 47 and 73% results in an increase of resistance between 12 and 31%. Can this be related to a definite percentage reduction in strength? If so, the deterioration of the conductor might be determined by a resistance test.

The degree of deterioration can show large variations over short distances, and several samples of the conductor might have to be taken to obtain accurately the condition over the whole route. The jointing of deteriorated conductor is difficult and not desirable; when a sample had been taken from one section of the line and its condition determined, could comparative resistance tests be made to determine the condition of other sections of line?

I do not think that the deterioration of a conductor can be calculated by mathematical formula or from its position in a coastal or industrial area. Other factors, such as the position of the line relative to the prevailing weather, seem to play an important part. On the Lockfields–Southport line, which runs along the west coast, severe corrosion has occurred and the conductors were renewed some time ago. On the Lockfields–St. Helens line, however, in the same locality but running at right angles to the coast, the conductor is in considerably better condition. At Runcorn we have perhaps the most exposed and polluted position on the Merseyside, yet the conductors here have suffered considerably less deterioration than the other conductors further inland and in what appear to be more sheltered positions.

Dr. J. S. Forrest and **Mr. J. M. Ward** (*in reply*): We are very interested in the developments for protecting conductors which Mr. McKenna describes, and we hope that these will be successful. We think, however, taking all factors into consideration, that it will be difficult to find a means of protection better than greasing.

The possibilities of paints and enamels, mentioned by Mr. Grahame, have been considered, but we know of none which would withstand handling during erection without damage, or which would remain intact on the conductors for more than a few years. Silicone greases, which cost about £220 per hundredweight, have no obvious advantage over the greases mentioned in the paper, which cost £3–£4 per hundredweight. It is generally accepted that anodizing is more effective than chemical treatment in forming a protective oxide film on aluminium, but, as Mr. McKenna has stated, it is not practicable to anodize conductors.

The difficulties encountered with grease (*b*) during erection are recognized, but these should be much more than offset by the advantage of increased life of the conductors. However, other greases, less difficult to handle, can be used instead. All the greases are equally suitable for industrial or coastal conditions.

Corrosion products on conductors are eroded by wind and weather to give the flattened appearance to which Mr. Smith refers, but no appreciable direct erosion of the metal takes place in a clean atmosphere. We know of only two conductors which have broken as a result of deterioration; most corroded conductors are replaced in time to prevent actual breakage. The failures occurred, not because the steel had been corroded, but because the current was transferred from the corroded aluminium strands to the steel core, which failed through overheating.

In answer to Mr. Speke, the electrical resistance of a strand cannot be directly related to its tensile strength unless the corrosion takes the form of a uniform reduction of the cross-sectional area of the strand. Attempts have been made to determine the approximate condition of lines by measuring the resistance *in situ*, but these have not been very successful, owing to difficulties in making the measurement.

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Paper No. 1854 S
June 1955

HIGH-VOLTAGE TRANSMISSION DEVELOPMENTS IN SWEDEN

By ÅKE RUSCK.

(*Lecture delivered before the* SUPPLY SECTION *23rd February*, 1955.)

In 1893 the first 3-phase transmission system came into operation in Sweden. The distance involved was 7 miles and the voltage was 10 kV. It was one of the first 3-phase transmissions in the world. About 60 years later the first Swedish 380 kV line was energized; this was at the beginning of 1952. Between these two steps lies the history of high-voltage-transmission development in Sweden.

In 1908 we had reached 55 kV and in 1915 we reached 77 kV. Our first 132 kV line came into operation in 1921, and in 1936 it was necessary to introduce 220 kV transmission. Fig. 1 shows

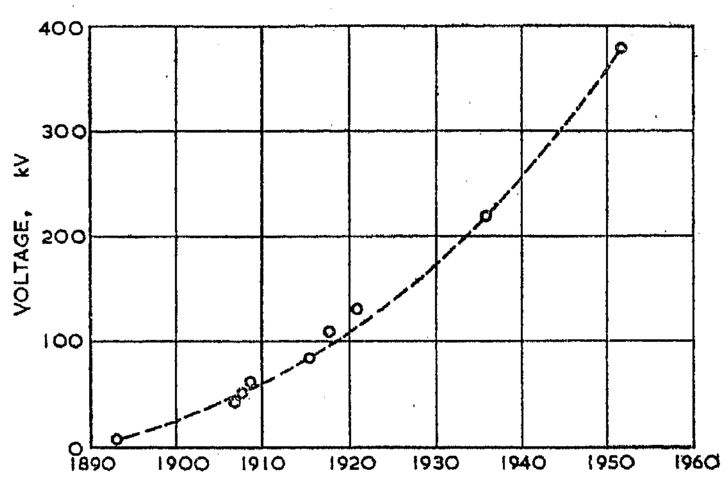

Fig. 1.—Introduction of new voltages in Sweden.

the introduction of new voltages, and it can be seen that the dotted line connecting the points is continuous and is quite like a load curve. It is no use calculating the number of years in which the voltage has doubled, as is generally done in Great Britain, and it is of minor value to make a forecast of the future development by extrapolating the curve.

We have not always had the highest transmission voltage in Sweden, but we have always been in the forefront, since our natural conditions have made it necessary to increase the transmission voltages at quite a rapid pace.

Sweden is a large country. The distance from the south to the extreme north in the Arctic zone is 1 000 miles. This is about 60% more than the distance from southern England to northern Scotland. Sweden is, however, a sparsely populated country. We have only seven inhabitants per square mile compared with 80 in the United Kingdom. Coal, oil and natural gas are almost entirely lacking in Sweden, but hydro-electric power resources are large. There are possibilities of harnessing about 80 000 million kWh a year, which corresponds to 11 000 kWh per year per head of the population. At present, about 24 000 million kWh a year is harnessed, which corresponds to about one-third of the economically-available resources. The production of electric power in 1954 corresponded to 3 300 kWh per head of the population. This figure is about the same as that of the United States, but lower than that of Norway and Canada.

The population is concentrated in the southern part of the country, where about 85% of the population live, but the hydro-electric resources are concentrated in the north. In the southern provinces you will find only 15% of the potential hydro-electric power resources, but the dominating power consumption is to be found in the comparatively densely-populated southern part, and this results in a big power transport from the north to the south over distances of 300–1 000 miles. This is why the problems of power transmission are so important in Sweden.

The power supply in the country is not nationalized. When electrification commenced in the early years of this century, the State and municipal and private enterprises started the work. Through the State Power Board—an independent business enterprise—the State is at present responsible for about 40% of the production of power, and the remaining 60% is provided by a number of private and municipal enterprises, each considerably smaller than the State Power Board. All the power enterprises are voluntarily co-operating in a special organization called the Central Operating Management, and all power plants are continuously operated in parallel.

The main portion of the 220 kV network and the whole of the 380 kV network are owned by the State Power Board, and under a special agreement, the present private 220 kV lines are operated by the State Power Board. This arrangement has been made in order to ensure a rational utilization and extension of the main network and to enable full advantage to be taken of the 380 kV system. On the other hand, the State Power Board is transmitting power for the large private enterprises. Sweden can thus be regarded as a unit when referring to high-voltage power transmission.

In 1946 the 220 kV network for transmission of power from the north to the south comprised four parallel lines with two further lines under construction (see Fig. 2). The extension of the 220 kV transmission system progressed very rapidly, and we found that it would be necessary to add a new 300-mile line every year. It was obvious that we had to contemplate a transmission system with a capacity considerably greater than that of the 220 kV network in order to decrease the transmission cost and save land required for rights-of-way. The necessity became all the more apparent when it was decided in 1946 to start harnessing our biggest hydro-electric project north of the Arctic circle, 600 miles from the consumption centre in the south of Sweden.

The use of high-voltage d.c. transmission was considered, but despite the promising results achieved at the experimental station, it was evident that the development of the d.c. system would not progress sufficiently rapidly to permit its use on a large scale in the very near future. Investigations were therefore confined to the use of a.c. transmission at voltages above 220 kV, and after careful study it was decided in December, 1946, to adopt 380 kV for a 600-mile line which was to come into operation at the beginning of 1952. Later, the voltage level of this system was defined in such a manner that the maximum service voltage was fixed at 400 kV.

In order to avoid extension of the 220 kV network it was necessary to make special arrangements to increase the transmitting capacity of the existing network. This was done by introducing, in 1950, a series capacitor for the first time in a 220 kV line and by using the first 380 kV line for 220 kV transmission from the beginning of 1951. That time schedule allowed four years for the investigation, design and construction of the 380 kV system, and with our limited resources this meant hard work.

One of the first things to be considered was the insulation

Mr. Rusck is with the Swedish State Power Board.

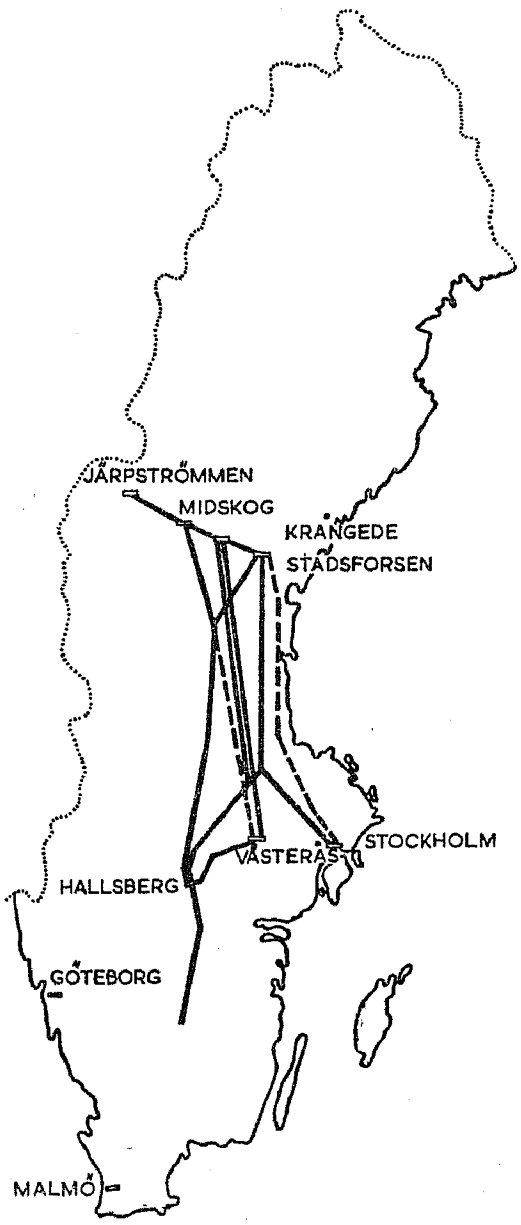

Fig. 2.—The 200 kV transmission system in 1946.

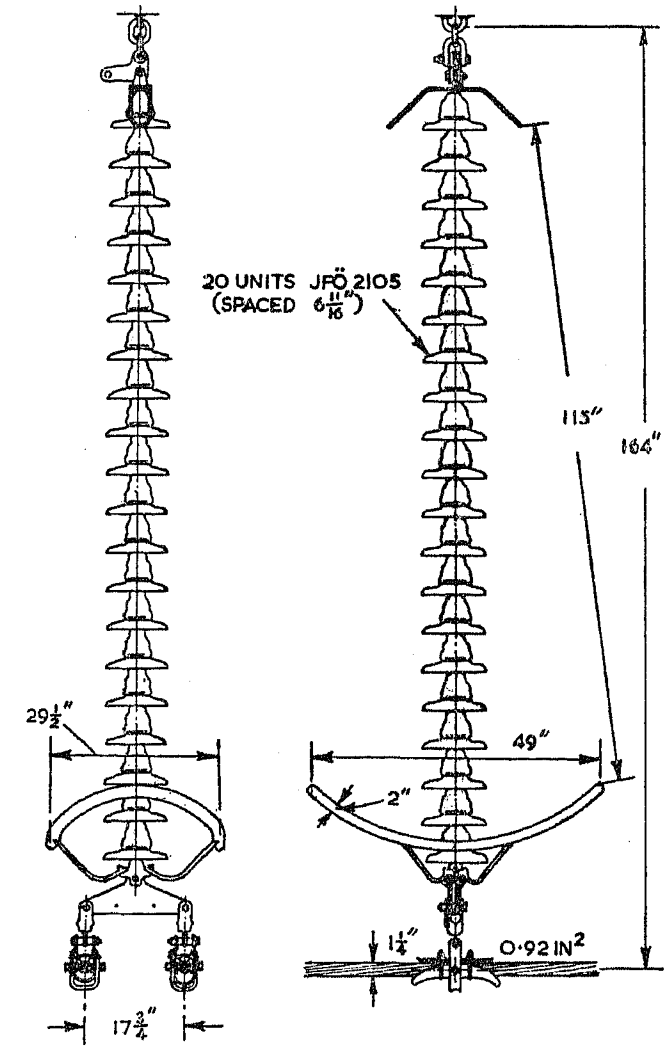

Fig. 3.—380 kV isolator string with grading ring.

level. Owing to the adverse combination of low short-circuit power and long transmission lines, exceptionally high 50 c/s voltages were set up in the first 380 kV line under certain switching conditions. Calculations showed that the lowest insulation level was about 1 550 kV for apparatus in the immediate vicinity of surge arresters and 1 750 kV for plant equipment situated within reasonable distance of the arresters. Taking the cost of different insulation levels into consideration, we decided to use 1 775 kV for transformers, circuit-breakers and other switchgear equipment. We were aware that it would be possible to reduce the insulation level when the system reached the stage at which internal over-voltages were reduced to a certain limit. In the extensions which came into operation in 1954, the insulation level for station equipment was reduced to 1 500 kV except for circuit-breakers and measuring transformers.

When the fundamental data had been fixed, the development and manufacture of the transformers, circuit-breakers and the majority of the remaining electrical equipment was commenced.

The line insulation was determined by the requirement that it should provide adequate safety against flashovers due to lightning or switching surges and that the lowest line insulator unit should not be subjected to excessive voltage stresses. The insulation level chosen for the first two lines was 1 600 kV, while for the rest we have reduced the insulation level to 1 500 kV. A special grading ring was developed in order to reduce the voltage stress across the bottom units (see Fig. 3).

It was important to design the power line so that corona losses and radio interference might be kept within suitable limits. The dimensions and arrangement of the conductors were determined after extensive experimental investigations on a test line. We decided to use double conductors with 18 in spacing, and each steel–aluminium cable has a diameter of 1¼ in. The double conductors have the advantage over single conductors of large diameter, besides reducing corona losses and radio interference, that they reduce the line reactance by as much as 26%. This increases the line stability. Bundle conductors comprising three or four cables per phase would, of course, further reduce the reactance, corona losses and radio interference, but these gains did not outweigh the additional cost and complication of design. It is possible that a third cable may be added in the future in order to reduce the resistive losses if high series-capacitance compensation is used.

The phase conductors are suspended from steel towers of an H-frame type (see Fig. 4). The two legs and the cross-arm are of welded design. For the new lines now under construction we use the same type of tower but of a bolted design. The standard span is 1 080 ft, and the height of the cross-arm above ground level is normally about 75 ft; the spacing between the phases is 39 ft. It has been necessary to introduce spacers between the two cables in each phase at a distance not exceeding 430 ft.

The first 380 kV line runs from Harsprånget in the north to Hallsberg in central Sweden (see Fig. 5), where we have a transformer station to convert the voltage to 220 kV. At Midskog, in the middle of the line, there is a transformer station connecting the 220 kV network with the 380 kV one. It was an exciting moment when, after extensive tests, the system was energized at 380 kV for the first time in April, 1952. Now we should know whether the system would work according to our calculations. I am glad to state that we were not disappointed; everything went smoothly, and we could look to the future with confidence.

It had not been possible to wait for the final test of the first line before commencing the construction of new 380 kV lines and substations. Two years previously we had started work on

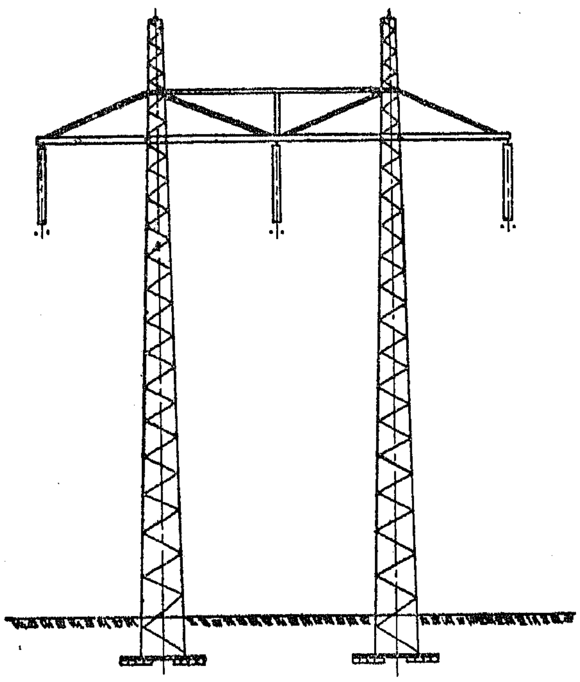

Fig. 4.—Tower for the second 380 kV line.

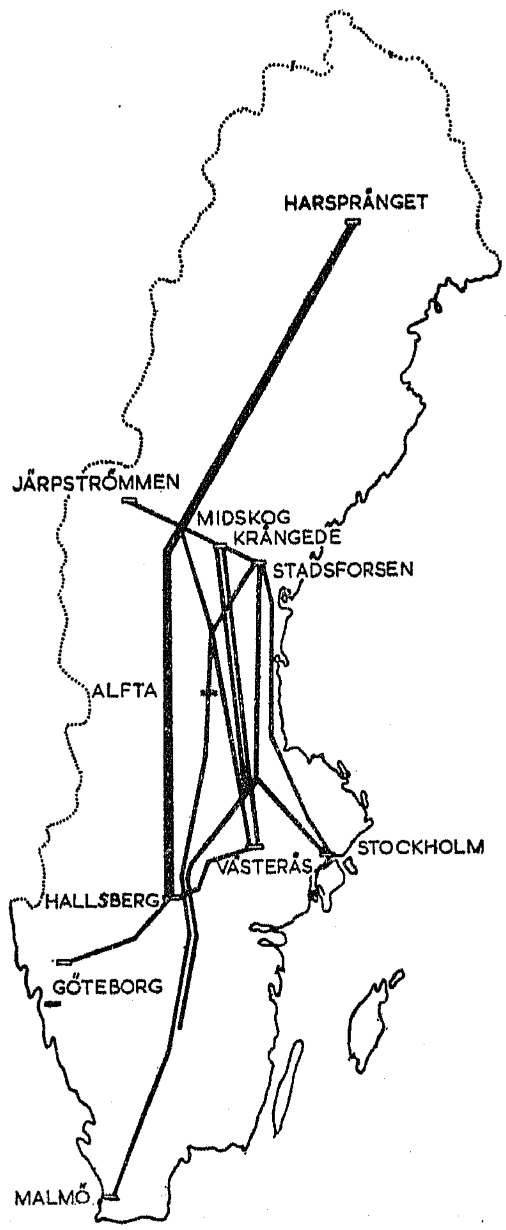

Fig. 5.—200 kV transmission system in 1952.

220 kV
380 kV

the second line, and at the same time we had decided to extend the first line to the southern part of Sweden. The system in operation in 1955 is shown in Fig. 6; it comprises 1 200 miles of 380 kV line.

In 1956 we shall have a third line from the north to the south in operation, and some extensions of present lines will come into operation in 1957 and 1958 (see Fig. 7). In 1958 the system

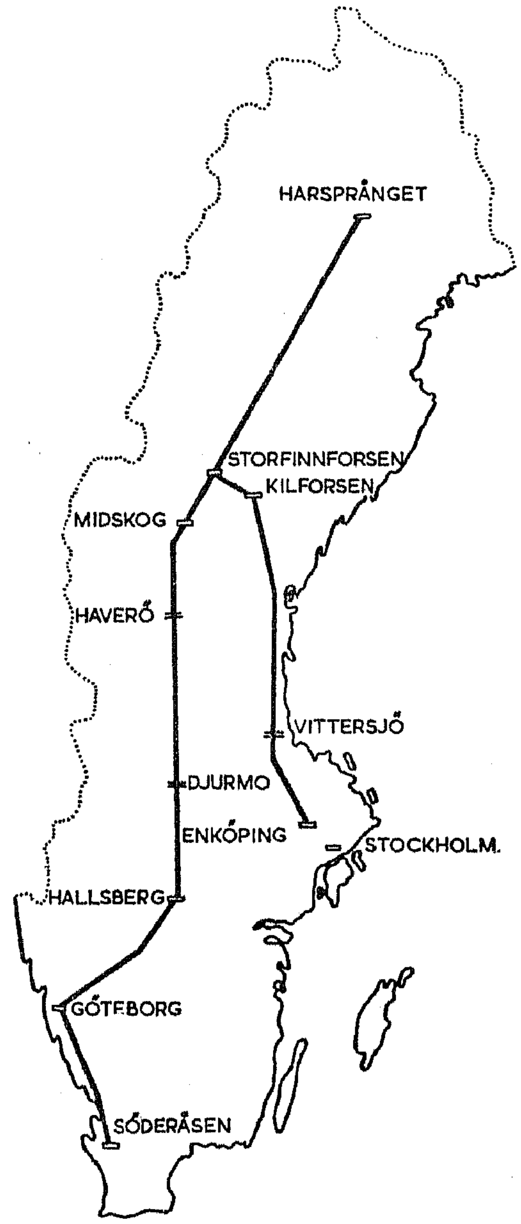

Fig. 6.—380 kV transmission system in 1955.

will comprise 1 900 miles of 380 kV line, and the total capacity of the transformer stations will be 8 000 MVA. We are now investigating the construction of a fourth line from the north to the south; it is preliminarily scheduled to come into operation in 1960.

In 1954 we introduced two series-capacitor stations in the first 380 kV line. The compensation, corresponding to 44% of the line reactance, raises the stability limit from about 450 to 700 MW. In the second line a 30% series capacitor will be inserted this year. Each capacitor station has a capacity of about 100 MVA.

We have utilized full-winding step-up transformers and auto-connected step-down transformers in all substations except that at Midskog; they are of the single-phase type, and the first groups for 380/220 kV are rated 300 MVA. The transformers installed in 1954 have a capacity of 510 MVA at 380/130 kV; they are the largest transformers ever built. In a new power station we also have two 3-phase 380 kV transformers each rated at 100 MVA. Most of the transformers are placed underground, and are connected with the outdoor switchgear by means of 380 kV cables. At the start, we used bushings both for the transformers and the cables, but in the new installations, the cable goes directly from the transformers without any bushings.

The circuit-breakers for the first system were all of the air-blast type with a rupturing capacity of 8 000 MVA at 350 kV. Minimum oil circuit-breakers have also been used. We now specify a rupturing capacity of 12 000 MVA. The total time for relay protection on air-blast circuit-breaker operation is about 0·10 sec, and the over-voltages produced by the circuit-breakers are less than 2·5 times the voltage to earth prior to interruption.

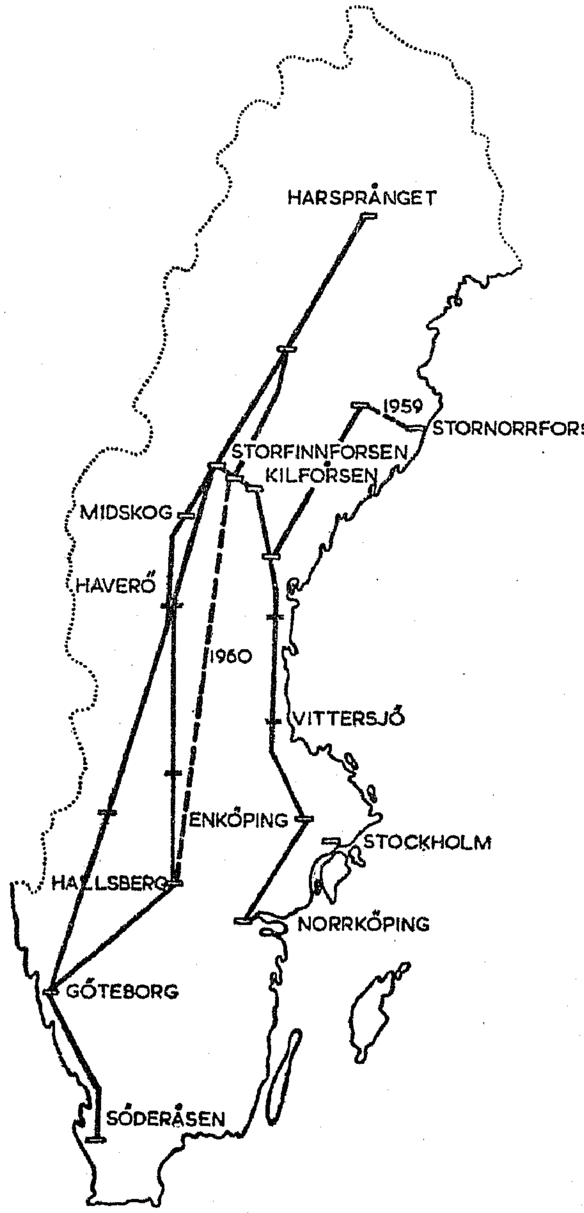

Fig. 7.—380 kV transmission system in 1958.

Automatic high-speed reclosing has been introduced and so far has functioned well.

The voltage in the stations is normally maintained at 400 kV, and in order to control the reactive power and maintain the voltage at the desired level, we use reactors and synchronous condensers. The corona losses average about 2 MW in a 300-mile line. The radio interference is of no importance to radio receivers situated more than 100–300 ft from the line. In order to improve receiving conditions, we are feeding the lines with the national broadcasting programme, and the lines are then used as antennae.

In various quarters, especially in the United States, there has been a certain scepticism about the use of bundle conductors. Our experiences are quite in their favour; they have reduced the corona losses and radio interference to harmless levels, and furthermore they have reduced the line reactance to a considerable degree. We have had no mechanical troubles. When, in some cases, we have had a heavier ice load on one of the cables, there has been a tilting, but as soon as it has fallen off, the conductors have reverted to their normal position without any permanent twisting or mechanical damage.

The line was calculated to carry a superimposed load on each cable of up to $2\frac{3}{4}$ lb/ft. On some spans exposed to exceptionally heavy icing we have found ice loads exceeding this value. These occasions are, however, very exceptional, and we have control of the situation by a continuous measurement of the damping of the carrier-current signal. On some occasions, we have removed the ice from the live line by using polythene ropes, which are swept along the conductors. We are contemplating the erection of extra towers in four or five spans where icing conditions are particularly bad.

Up to the present we have had five single-phase and two 2-phase outages on the 380 kV system owing to lightning, which means 0·25 fault per 100 miles per year; this agrees well with the calculated value. All the lightning faults have been correctly cleared, and in several cases the lines have been automatically reclosed.

It is, of course, of no use introducing a new transmission system if you do not save money, and I must now mention the economy. It is not easy to compare figures of the first costs of installations between different countries, because you have to take into consideration many different factors. I do not intend to give absolute figures of the cost of the line, transformer stations, etc., but I will confine myself to the statement that, by introducing the 380 kV system and using series capacitors, it has been possible to reduce the transmission cost per kilowatt including losses by about 40% compared with 220 kV transmission. This is quite appreciable, and was certainly worth the risks involved in the development of the new system.

At the same time as the development of the 380 kV system was proceeding, we were also engaged on a high-voltage direct-current scheme. We did, of course, hesitate a little about dividing our energies on two new systems at the same time, but by the enthusiasm and hard work of our small staff of specialists the difficulties were overcome.

The ASEA Co. has been engaged since 1930 on the development of a mercury-arc convertor which could be employed for high voltages. In 1943, collaboration was initiated between the ASEA Co. and the State Power Board with the object of extending this experimental work, particularly in the testing of new designs. The two concerns together set up a laboratory for high-voltage direct current, and work has been carried on there continuously since the autumn of 1945.

The interest of the State Power Board in the development of the high-voltage d.c. system was partly concerned with the transmission of power to the Island of Gotland in the Baltic Sea, but it was largely based on a desire to ascertain the possibilities of constructing an economic system for transmitting large quantities of power over long distances.

The development work has been directed towards the production of a suitable mercury-arc convertor, i.e. an electrically-connected combination of ionic valves. The valves used for the Gotland transmission operate, in principle, like normal mercury-arc rectifiers. The novel feature consists in the high working voltage. Formerly, voltages were limited to a maximum of about 3 kV, whereas 50 kV is now adopted for the valves used for the first transmission of power. The Island of Gotland is situated about 60 miles from the mainland, and it was impossible to use alternating current for such a long submarine cable. The power is supplied from the 132 kV network to Västervik, where a convertor station has been erected. The incoming voltage of 132 kV is stepped down in two 3-phase transformers to 40 kV, which is fed into each of the two series-connected valve sets. The latter then each supply 50 kV d.c., i.e. 100 kV together, to the cable. The current is received by the other convertor station, which is located a few miles south of Visby. At this point the direct current is reconverted into alternating current and transformed to 33 kV, which is the primary distribution voltage hitherto employed on Gotland.

A number of ionic valves are employed in each station, connected in two sets comprising seven valves each. The current normally flows through six of the valves. The seventh valve comes into operation only in the event of faults occurring in any of the others. The most serious fault that may arise in the valves is their loss of capacity to block the current flow in one direction. A partial short-circuit in the connected network then occurs. In such cases, arrangements are made for the six

operating valves to be blocked through their control grids, whereupon the seventh valve immediately opens a parallel path for the current. This cuts off the current from the six-valve group affected, and gives it an opportunity of regaining its working capacity. After a short interval the six valves are unblocked again automatically, and the convertor functions in the normal manner once more. The whole procedure takes place in less than half a second, and an interruption of such short duration will not be perceptible in the Gotland network. Each set of valves has an energy output of 10 000 kW, and thus the total transmission capacity is 20 000 MW at 100 kV.

Transmission between the convertor stations is carried out by means of a single conductor only, the current being returned through the earth and water. This system was chosen in order to reduce the cost of the cable, which would otherwise have required two conductors. The current is conducted to earth at two electrode stations. In order to prevent the current from the electrodes passing along the cable to an excessive extent, which would result in corrosion of the cable armouring and lead sheath, it was necessary to locate the points for the electrodes about six miles to the south of the cable. Comparatively simple overhead lines connect the electrodes and the convertor stations.

The d.c. cable (see Fig. 8) is 60 miles long and has a single

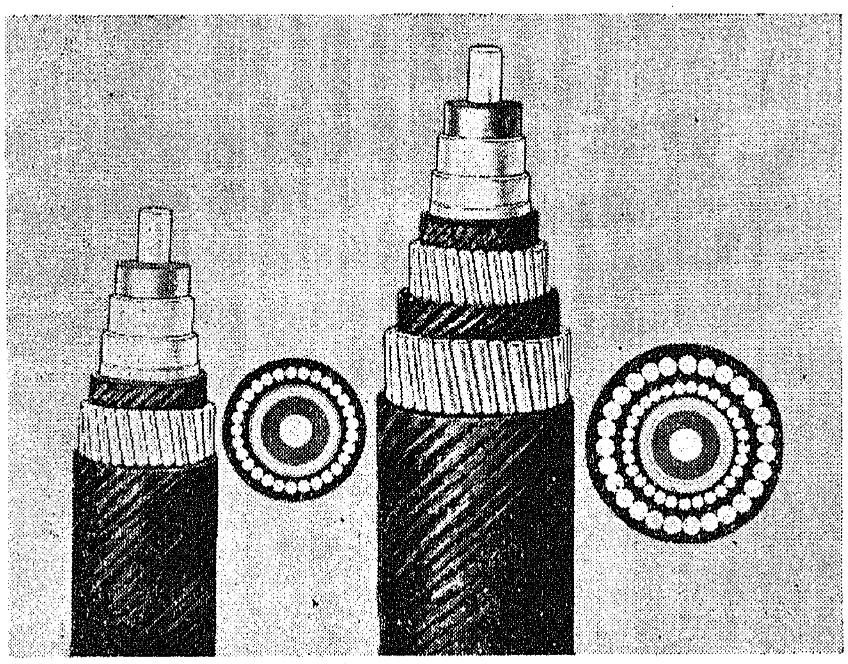

Fig. 8.—Cross-section of 100 kV d.c. cable.

core with a conductor area of $0 \cdot 14 \, in^2$. It is immediately surrounded by the insulation, which consists of a 7 mm thick layer of thin paper tapes wound on the cable and impregnated with heavy oil. Two lead sheaths are placed over the paper, one of which is pressed on to the other. A double lead sheath has been employed in order to reduce the risk of a through-hole, which may sometimes be formed in the course of production when any irregularities are present in the lead. The outside is served with an armouring consisting of one or two layers of steel wire and a covering of jute. Double armouring is used only on those parts of the cable which lie nearest to the land and are thus more exposed to the risk of damage from drifting ice, ships' anchors, etc.

From the outset it was desirable that the cable should be constructed in such a manner that as few joints as possible would have to be made when laying it in the sea. It was found possible subsequently to reduce the number to the absolute minimum owing to the fact that it is always desirable to begin the laying on land, i.e. a single joint. In order to achieve this advantage, however, numerous problems had to be solved in connection with the manufacture and storage of the long cable lengths in the factory and their transport and loading on board the cable ship. The laying of the cable took place during May and June, 1953. The long cable lengths, which weighed 300 and 600 tons, respectively, rendered the employment of a comparatively large cable-laying vessel necessary. The choice fell on the British Post Office cable ship *Alert*. A detailed programme was drawn up, and owing to exceptional luck with the weather during laying and the skill of the captain and the crew of the *Alert*, the work was carried out in close approximation to the timetable planned. It took only 16 days from the beginning of loading the cable on to the ship up to the day for clearing the cable ship for the return voyage to England.

The operation of the d.c. transmission is supervised from Visby. The current normally flows in the direction from Västervik to Visby, and it is therefore necessary to regulate the transmitted energy in such a manner that it corresponds exactly to the consumption in the Gotland network. This is effected automatically, inasmuch as the energy transmitted is regulated by the frequency of the a.c. network on Gotland. The convertors both at Visby and Västervik must be controlled, which necessitates a remote control system carried out via a radio link.

According to the original plan, the Gotland power transmission was to come into operation with one convertor only in each station at the beginning of 1954, while the other convertors were to be commissioned in the middle of the same year. On the 7th March, 1954, the erection had advanced so far that we were ready to start test operation. Once again we had a moment of great excitement similar to that at the start of the 380 kV system. The transmission started, and it worked according to our calculations. During the first days the transmitted power was limited to 2 000–4 000 kW.

After two weeks of operation a fault occurred on the cable, and it was located to a point 34 km from Västervik. Owing to unfavourable weather conditions the repair was delayed, and it took three weeks before the cable was again ready for operation. The fault was due to mechanical damage to the cable.

At the beginning of April, 1954, when the cable had been repaired, operation was resumed. From the 12th April until the last week of July the d.c. transmission was in continuous service, with a transmitted power in both directions of up to 10 000 kW, which is the rated load of a convertor set. On the 26th July the second convertor set was started, which increased the transmission capacity to 20 000 kW, and it even seems possible to overload it to 25 000 kW. I want to stress that the transmission is double-way, and it is very easy to change over from one direction to the other. Most of the time, of course, hydro-electric power is sent from the mainland to the Island of Gotland, but on some occasions when we have been short of water, we have fed steam-generated electric power produced on Gotland into the network of the mainland.

Another cable fault occurred on the 29th October, when a ship dropped its anchor on to the cable close to the mainland coast. This time it took seven days to repair the fault; however, we do not regard these two cable faults seriously. The first was probably due to the manufacture or the laying of the cable, and we hope to avoid faults caused by ships' anchors near the shore by taking special precautions. On the other hand, the most difficult elements in the transmission, i.e. the convertors, have behaved extremely well. There has been no trouble from commutation failures, and in this respect operational experience seems to be very reassuring. In October we carried out a series of short-circuit tests on the a.c. side of the inverter station. A total of 30 tests were made at different distances from the station, ten of them directly on the a.c. terminals of the station. The oscillograms taken showed that the inverters were capable of operating in a normal way also during the short-circuit period.

The first months of operation of the Gotland transmission have been quite successful and the results obtained from the

comprehensive research and development work, on which this project is based, have been confirmed. I think you may consider that the problems of high-voltage d.c. transmission have now been solved.

The cost of the whole d.c. transmission system amounted to £1·3 million, of which £350 000 was expended on the cable. The total cost thus corresponds to £65 per kilowatt of transmission capacity. This is a high figure according to Swedish conditions, but nevertheless it permits a certain margin for lowering the power rates on Gotland. Furthermore, a very considerable increase in consumption is anticipated, which may afford the possibility of doubling the capacity of the plant at a relatively early date. This would enable the specific transmission costs to be appreciably reduced. We have also obtained a great deal of experience which will enable us to produce a simpler and thus cheaper design for a future transmission system.

We have made an estimate of the cost of a 100 MW 200 kV transmission system to Gotland, and have found that it would be £21 per kilowatt, i.e. only one-third of the specific cost of the system we now have in operation. If the cable length were reduced to that of the distance between England and France, the cost would be reduced to £18 per kilowatt.

Before concluding I want to say a few words about the future. What transmission system and what voltage will be used? Will the 400 kV level mark a limit, will we have an a.c. system for a considerably higher voltage, or will we have an extra-high-voltage d.c. system? If you believe in extrapolating curves you will find from Fig. 1 that in 1970 we should use a voltage of 650 kV. I do not believe in doing that, but I will relate something of what is going on in our research departments.

If, seven years ago, we had the knowledge that we have at present, I believe we would have chosen a higher voltage than 380 kV, probably 450 kV. The insulation level of the present 380 kV lines is a little on the conservative side and will allow an increase of the voltage to 500 kV when internal over-voltages have been reduced. In order to avoid radio interference, it will then be necessary to add a third conductor in each phase of the lines. The present transformers must be rewound or completed with booster transformers. This will be easier in the northern section of the system, where we have full-winding step-up transformers from the generating voltage, than in the southern part where auto-transformers are mainly used. One solution would be to use 450 kV at the transmitting end in the north and let the voltage gradually drop to 400 kV at the receiving end in the south. The matter is now being thoroughly studied, and it is not out of the question that one day the voltage of the present 400 kV system will be increased to the 450–500 kV level, at least in some parts of the system.

At the same time we are also investigating a new system with a considerably higher voltage. We have found that a voltage of about 650 kV is probably the highest we may consider. We are investigating a 650 kV line using four bundled conductors. Such a line will have a transmission capacity of about 2 000 MW with series-capacitor compensation. With the four 380 kV lines running from the north to the south which will be in service in 1960, two or three 650 kV lines would be sufficient for all power transmission in Sweden in the future.

Another possibility would be to use e.h.v. direct current. Development work is proceeding in order to provide ionic valves for a higher voltage and a larger capacity than the valves used in the Gotland transmission, and the prospects seem favourable. We are now making calculations on a d.c. system for ±400 kV. Such a line would have about the same transmission capacity as the 650 kV a.c. line, or nearly 2 000 MW. It is, at present, impossible to provide any figures for comparison. Figs. 9 and 10 give a comparison of the towers for 650 kV a.c. and ±400 kV d.c.

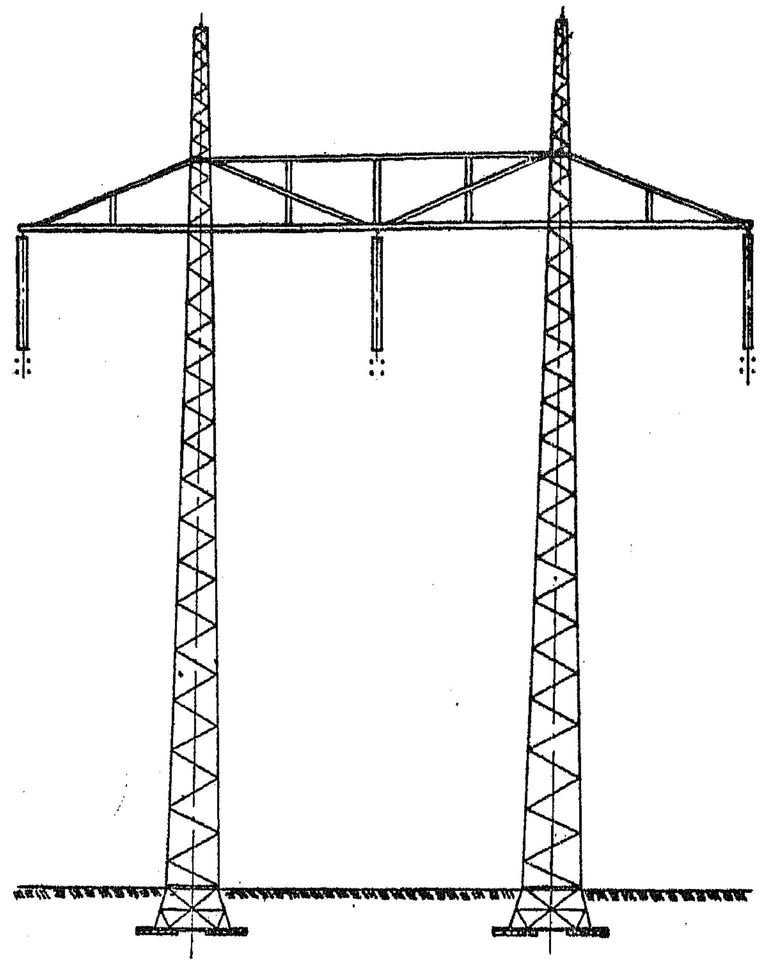

Fig. 9.—Tower for 650 kV a.c. system.

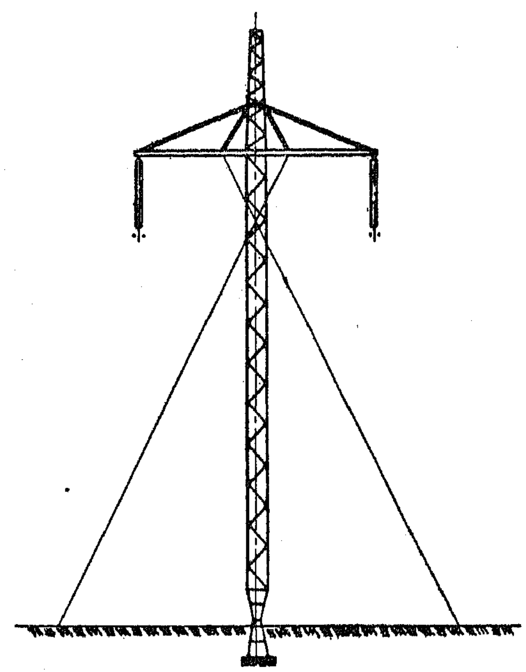

Fig. 10.—Tower for ±400 kV d.c. system.

The a.c. and d.c. transmissions each have their own special advantages, and a final solution will require considerable economic and technical comparisons.

I am not quite sure that we really need a new super-super system. Our potential hydro-electric resources in the northern part of the country have been recalculated, and the figure is about twice as high as when we decided on the voltage of 380 kV. On the other hand, the transmitting capacity of a 380 kV line has been increased by using series capacitors. Furthermore, the load is increasing in the northern districts, and in 10–20 years' time nuclear power plants may take care of some load in the southern regions. Anyhow, if and when we need a new transmission system with a considerably higher transmission capacity, I am sure that our transmission specialists will be glad to embark on the new problems involved in such a development.

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SINGLE-PHASE 50 c/s A.C. TRACTION USING A RECTIFIER

By A. MANDL, D.Sc.Tech.

(*The paper was first received* 14*th September, and in revised form* 17*th November*, 1954.)

SUMMARY

The paper explains some of the problems arising when a traction motor is fed from an a.c. supply through a single-phase rectifier. The output voltage of the rectifier contains an a.c. component (ripple voltage) of twice the line frequency. It is shown how the ripple voltage depends on the commutating reactance of the rectifier circuit for various load conditions. The effect of the a.c. component (ripple current) in the motor current and the effect of the degree of smoothing necessary to reduce this ripple current on the commutation and commutator-bar voltage of the motor and on the waveform of the line current are examined. Methods whereby these effects may be reduced to a permissible value are investigated, and the influence of such modifications on the commutation and transient stability—short-circuits and interruptions—are analysed. Oscillographic and other tests carried out on a few traction motors modified in different ways are shown to confirm the theory developed. In the case of a machine with a solid frame, i.e. without laminated magnetic shunt to the compole circuit, certain d.c. commutating conditions must be fulfilled to ensure acceptable commutation when the motor current contains a ripple component.

LIST OF SYMBOLS

θ = Angle of overlap.
k = Transformer ratio.
k_r = Transformer ratio at rated output.
V_p = Primary supply voltage (r.m.s.).
V = Transformer output voltage at no load per anode (r.m.s.).
V_r = Value of V at transformer ratio k_r.
V_d = Direct voltage.
V_{dr} = Value of V_d for rated output.
V_{sh} = Short-circuit voltage (r.m.s.).
ΔV_c = Voltage drop due to commutation.
ΔV_R = Voltage drop due to resistance.
V_{100} = Peak 100 c/s ripple voltage at the terminals of the rectifier.
V_{100m} = Peak 100 c/s ripple voltage at the terminals of the motor.
V_m = E.M.F. of motor.
I_p = Rated primary transformer current (r.m.s.).
I = Motor current.
I_r = Rated motor current.
I_f = Current in field winding.
i_c = Short-circuit current during commutation of rectifier.
I_{100} = Peak 100 c/s ripple component in motor current.
$\rho = I_{100}/I$.
I_{100f} = Peak 100 c/s current in field winding.
X_c = Commutating reactance.
$L_c = X_c/\omega$ = Commutating inductance.
X'_c = Percentage commutating reactance.
X_w = Reactance of contact wire.
X'_w = Percentage reactance of contact wire.
ΣL = Total inductance in d.c. circuit.
X_f = 100 c/s reactance of main field winding.
L_f = 100 c/s inductance of main field winding.
R_p = Resistance of transformer primary winding.
R_s = Resistance of transformer secondary winding per anode.
R_w = Resistance of contact wire.
Φ = Magnetic flux of motor.
p = Number of pairs of poles.
f_a = Armature frequency.
N_c = Number of commutator bars.
β = Ratio of pole arc to pole pitch.
N_a = Number of armature turns per circuit.
N_p = Numbers of compole turns.
$\alpha = N_p/N_a$.
N_f = Number of field turns.
R_f = Resistance of main field winding.
R'_f = Percentage resistance of main field winding.
R_d = Resistance of diverter to main field winding.
x = Compole divert, %.
y = Compole boost, %.

(1) INTRODUCTION

Among the schemes which are considered for railway traction from single-phase alternating current, the rectifier scheme comes nearest to d.c. traction. Output voltage and current from the rectifier consist of a useful d.c. component which produces the motor torque and an a.c. component in which the fundamental frequency of twice the line frequency is predominant. The a.c. component is rather troublesome, but is unavoidable because of the peculiarity of single-phase rectification.

The output voltage of a single-phase rectifier is in principle a commutated sine wave, as shown in Fig. 1. During the period

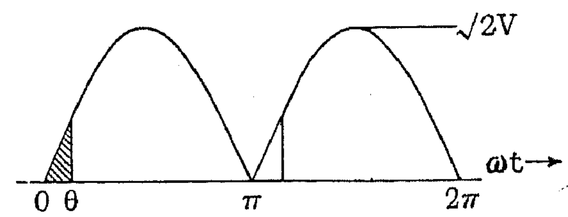

Fig. 1.—Waveform of rectified transformer output voltage V.

of overlap from $\omega t = 0$ to θ, both anodes are conductive and the output voltage is zero.

In the principal connection diagram of Fig. 2, the current I is assumed to flow from anode 1 to the cathode. When the transformer voltage is reversed, anode 2 also becomes conductive

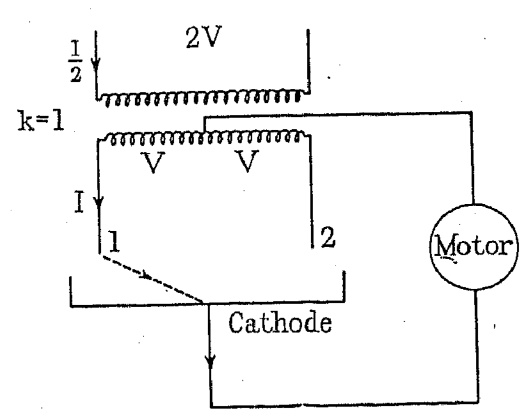

Fig. 2.—Supply transformer—rectifier—traction-motor circuit.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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and the transformer is short-circuited. The short-circuit current opposes the current from anode 1 to the cathode and transfers it gradually to anode 2.

The transformer output voltage (r.m.s., at no load) per anode is V. If we assume the transformer ratio k to be unity the supply voltage is $2V$. The secondary current I flows in half the secondary winding only, and the primary current is therefore $I/2$.

Figs. 3A and 3B show two typical oscillograms taken on the

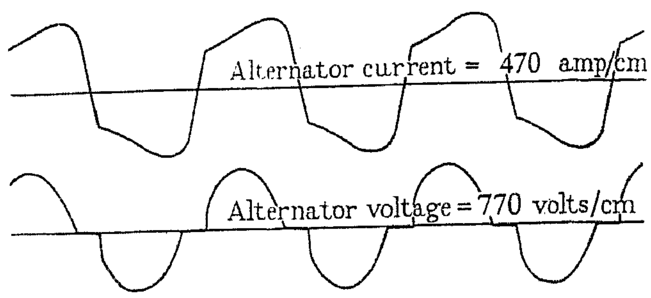

Fig. 3A.—Oscillogram of primary voltage and current supplied to transformer.

Motor at 420 volts 152 amp. Two choke coils in series. Divert, 62%.

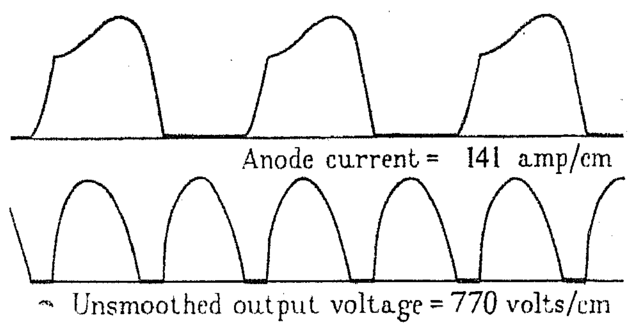

Fig. 3B.—Oscillogram of anode current and output voltage of rectifier.

Motor at 420 volts 152 amp. Two choke coils in series. Divert, 62%.

test arrangement. The lower curve of Fig. 3A is the output voltage of the alternator which feeds into the primary winding of the transformer. During the period of commutation the alternator, which is short-circuited through the transformer, has zero voltage. If the negative half-waves are reversed the rectifier output voltage is obtained, which is the lower curve of Fig. 3B. The top curve in Fig. 3B represents the current per anode.

(2) RECTIFIER AND SUPPLY TRANSFORMER

(2.1) Commutating Reactance

The commutation in the rectifier is a repetitive transient during which the secondary winding is short-circuited. The commutating reactance is identical with the total leakage reactance of the transformer and can be measured by making a short-circuit test as indicated in Fig. 4. The voltage V_{sh} has to be

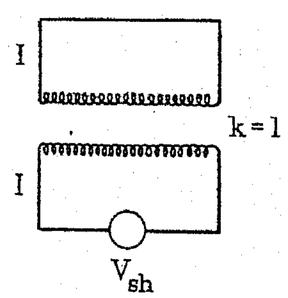

Fig. 4.—Connection for short-circuit test of transformer.

applied to the total secondary winding to drive the current I in both windings. The commutating reactance is then

$$X_c = \frac{V_{sh}}{I} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It is usual to express the total leakage of the transformer as a percentage of the rated load impedance of the primary side. The primary winding does not undergo any change throughout the cycle, whereas the secondary winding changes from short-circuit between phases to single-phase load. The transformer ratio, k, in Fig. 5, is k_r for the rated output. Tractive effort

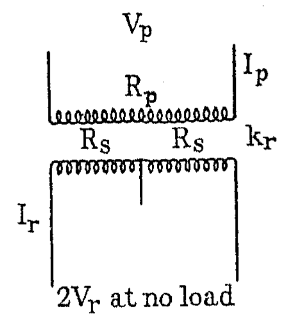

Fig. 5.—Schematic of transformer for rated output.

(current) and speed (voltage) are specified for the rated output. These values are obtained with the transformer ratio k_r. The normal supply voltage from the contact wire to the primary winding is V_p, and the rated primary current is I_p.

The commutating reactance X_c, referred to the secondary side of the transformer, can be expressed as $X_c'\%$ of the load impedance:

$$X_c = \frac{X_c'}{100} \times \frac{V_p}{I_p} \times \frac{1}{k_r^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Substituting for V_p the no-load transformer output voltage per anode at the transformer ratio k_r for the rated output,

$$V_p = 2V_r k_r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and for the rated primary current I_p, substituting the rated secondary anode current I_r,

$$I_p = \frac{I_r}{2k_r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

the total leakage or commutating reactance is

$$X_c = \frac{X_c'}{100} \times \frac{4V_r}{I_r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Eqn. (5) is applicable to any kind of transformer arrangement with voltage regulation by tappings on the primary or secondary side. X_c is the commutating or leakage reactance defined by the short-circuit test of Fig. 4 for the transformer connection under consideration. V_r is the secondary no-load voltage per anode for the transformer ratio k_r which corresponds to the rated output, and I_r is the rated motor current. The commutating reactance, which varies greatly for different tappings, is expressed in eqn. (5) as a percentage X_c' of the same impedance $4V_r/I_r$, which according to eqns. (2), (3), and (4) is identical to the primary load impedance for the rated output referred to the secondary side. The commutating or leakage reactance X_c and the percentage leakage reactance X_c' are, in general, different for every tapping.

The reactance X_w of the contact wire has to be included. V_p is then the rated voltage kept constant at the substation.

X_w can be expressed in the same way as a percentage X_w' of the rated load impedance and referred to the secondary side as follows:

$$X_w = \frac{X_w'}{100} \times \frac{V_p}{I_p} \times \frac{1}{k_r^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

X_c' in eqns. (2) and (5) therefore has to be replaced by the sum of the percentage leakage reactance of the transformer and the percentage reactance of the contact wire.

(2.2) **Angle of Overlap**

The voltage which drives the short-circuit current i_c during the period of commutation is $2V\sqrt{2}\sin\omega t$. V is the secondary no-load voltage per anode. The inductance in the circuit is

$$L_c = \frac{X_c}{\omega}$$

Therefore $$2V\sqrt{2}\sin\omega t = \frac{X_c}{\omega}\frac{di_c}{dt}$$

The commutating period is finished when i_c has increased to I. This means

$$\int_{\omega t=0}^{\omega t=\theta} 2V\sqrt{2}\sin\omega t\, d\omega t = X_c I$$

and $$\sin\frac{\theta}{2} = \frac{1}{2}\sqrt{\left(\frac{X_c I}{V\sqrt{2}}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and substituting for X_c from eqn. (5)

$$\sin\frac{\theta}{2} = \sqrt{\left(\frac{1}{\sqrt{2}} \times \frac{X'_c}{100} \times \frac{I/I_r}{V/V_r}\right)} \quad . \quad . \quad . \quad (7a)$$

For the rated output $V = V_r$ and $I = I_r$,

$$\sin\frac{\theta}{2} = \sqrt{\left(\frac{1}{\sqrt{2}} \times \frac{X'_c}{100}\right)} \quad . \quad . \quad . \quad . \quad (7b)$$

For instance, for 10% reactance, $X'_c = 10$,

$$\sin\frac{\theta}{2} = \sqrt{\left(\frac{0\cdot1}{\sqrt{2}}\right)} = 0\cdot266, \text{ and } \theta = 31°$$

(2.3) **Voltage Drop Due to Commutation**

The shaded area in Fig. 1 represents the loss in volt-seconds per anode during the time of half a cycle, i.e. $1/2f$ sec.

The loss in volt-seconds in the whole secondary winding during half a cycle is

$$L_c I = \frac{X_c}{2\pi f} I$$

and per anode it is

$$\frac{L_c I}{2} = \frac{X_c}{4\pi f} I$$

The voltage drop ΔV_c per anode is obtained by dividing the loss in volt-seconds by the time $1/2f$ of half a cycle:

$$\Delta V_c = \frac{X_c}{2} \times \frac{I}{\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

If X_c is replaced by X'_c from eqn. (5)

$$\frac{\Delta V_c}{V_r} = \frac{X'_c}{100} \times \frac{2}{\pi} \times \frac{I}{I_r} \quad . \quad . \quad . \quad . \quad . \quad (8a)$$

It has to be mentioned that perfect smoothing of the direct current has been assumed. Only in this case is the maximum value identical with the r.m.s. value I.

For 10% total reactance, $X'_c = 10$, and rated current $I = I_r$

$$\frac{\Delta V_c}{V_r} = \frac{10}{100} \times \frac{2}{\pi} = 6\cdot36\%$$

(2.4) **Voltage Drop due to Resistance**

R_p = Resistance of the primary winding (see Fig. 5).
R_s = Resistance of the secondary winding per anode (see Fig. 5).
R_w = Resistance of the contact wire.
ΔV_R = Voltage drop due to resistance.

$$\Delta V_R = I\left(\frac{R_p + R_w}{4k^2} + R_s\right) \quad . \quad . \quad . \quad . \quad (9)$$

(2.5) **Direct Voltage calculated from Transformer Output Voltage V at No Load per Anode**

Besides the voltage drop due to commutation [eqn. (8)] and due to resistance [eqn. (9)] there is a voltage drop in the arc of the rectifier of approximately 20 volts, which is constant.

The direct output voltage of the rectifier is therefore

$$V_d = V\sqrt{2}\frac{2}{\pi} - \frac{X'_c}{100} \times \frac{2}{\pi} \times V_r \times \frac{I}{I_r} - I\left(\frac{R_p + R_w}{4k^2} + R_s\right) - 20 \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The direct supply voltage to the motor terminals is smaller by the voltage drop in the resistance of the smoothing choke coil.

An approximation to the direct output voltage of the rectifier is

$$V_d = V\sqrt{2}\frac{2}{\pi}\cos^2\frac{\theta}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

which considers only the first two terms of eqn. (10) and neglects the voltage drop in the resistance and in the arc.

(2.6) **Alternating Voltage Component of Twice the Line Frequency in the Rectifier Output Voltage**

The fundamental frequency of the unsmoothed output voltage of the rectifier, as shown in Fig. 1, is twice the line frequency—in this case 100c/s—and the peak value can be calculated by Fourier analysis.

The ratio of the peak voltage, V_{100}, of the 100c/s component to the no-load maximum, $V\sqrt{2}$, of the transformer output voltage per anode is plotted in Fig. 6, against the angle of overlap θ.

The 100c/s ripple can now be calculated for a few important cases.

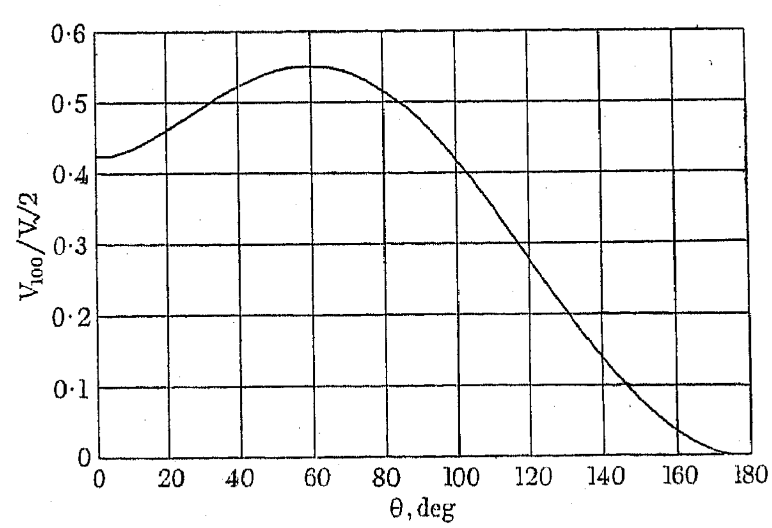

Fig. 6.—Ratio of peak value, V_{100}, of 100c/s ripple voltage to peak value, $V\sqrt{2}$, of no-load transformer output voltage per anode plotted against angle of overlap θ.

(2.6.1) **Rated Output $V = V_r$ and $I = I_r$.**

The angle of overlap follows from eqn. (7b) for different values of percentage reactance X'_c. With the help of Fig. 6 and eqn. (11) the ratio V_{100}/V_{dr} can be calculated. V_{100} is the peak value of the 100c/s ripple voltage, and V_{dr} the rated direct voltage. This ratio is plotted in Fig. 7 depending on X'_c. It rises approximately linearly from 75% for $X'_c = 5$ to 90% for $X'_c = 15$. The value of X'_c is therefore not very critical for the peak value of the

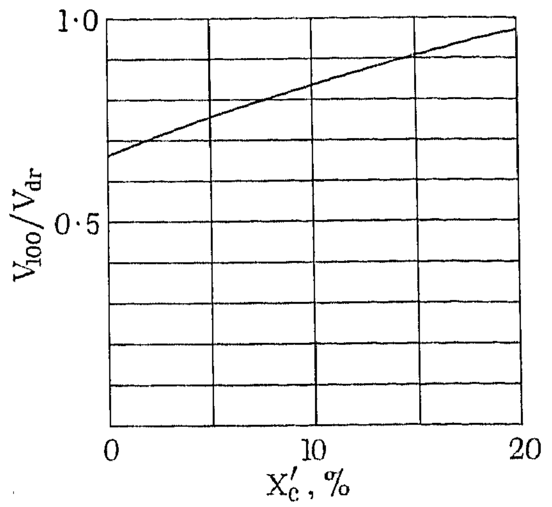

Fig. 7.—Ratio of peak value, V_{100}, of 100c/s ripple voltage to direct voltage, V_{dr}, at rated output plotted against percentage commutating reactance X_c'.

$V = V_r$ and $I = I_r$.

100c/s ripple component, and should be chosen to provide sufficient limitation of the transformer short-circuit current.

(2.6.2) **Load Current is Constant and Direct Voltage is Variable.**

The ordinates in Fig. 8 are the ratio V_{100}/V_{dr}, i.e. the peak value V_{100} of the 100c/s ripple to the rated direct voltage V_{dr}, and the abscissa is the ratio V_d/V_{dr}. Three sets of curves have been plotted for three values of X_c', namely 5, 10 and 20%, and each set for $I/I_r = 0 \cdot 5$, $1 \cdot 0$ and $2 \cdot 0$. It must be remembered that X_c' is not constant in practice, as the output voltage is regulated by altering the transformer ratio k.

Fig. 8 shows that the peak 100c/s ripple voltage is approximately proportional to the direct voltage V_d.

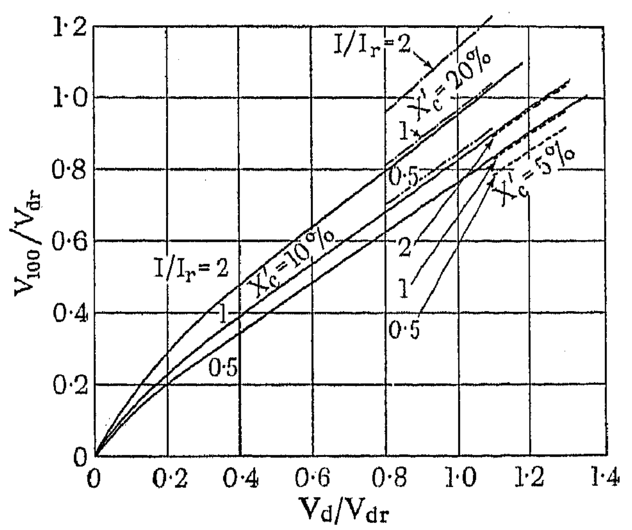

Fig. 8.—Ratio of peak value, V_{100}, of ripple voltage to rated direct voltage V_{dr}, plotted against the ratio of direct voltage V_d to rated direct voltage V_{dr}, for percentage commutating reactances $X_c' = 5$, 10 and 20% and for direct currents of 0·5, 1·0 and 2 times the rated direct current I_r.

(2.6.3) **No-Load Voltage V is Constant and Current I varies from Zero to $1 \cdot 5I_r$.**

In Fig. 9 the ratio $V_{100}/V_r\sqrt{2}$ is plotted, i.e. the ratio of the peak 100c/s ripple voltage to the peak rated transformer output voltage per anode, for two values of $V = 0 \cdot 5V_r$ and $1 \cdot 0V_r$, against I/I_r for $X_c' = 10\%$. The peak 100c/s ripple voltage rises slowly with the current, e.g. for $V = V_r$ from $I = 0 \cdot 5I_r$ to $I = 1 \cdot 5I_r$ it rises from 45·5 to 51·5% respectively.

For 10% total reactance the peak 100c/s component of the unsmoothed output voltage of the rectifier is, at the rated output, 84% of the direct voltage, and is not sensitive to a change of X_c' (see Fig. 7). If at a constant current the direct voltage is reduced, the peak ripple voltage falls approximately in proportion (see Fig. 8). If the supply voltage is constant and the current varies, the peak ripple voltage changes much more slowly than the current owing to the ripple voltage which still exists at zero current (see Fig. 9).

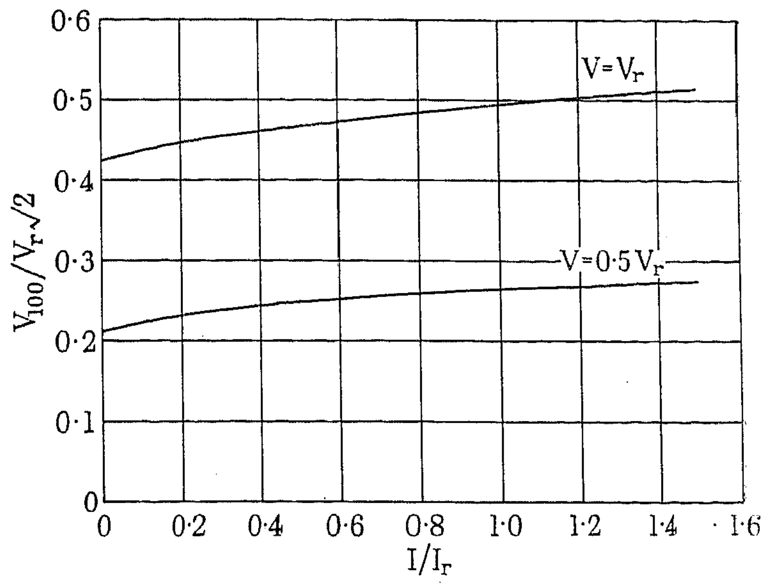

Fig. 9.—Ratio of peak value, V_{100}, of ripple voltage to peak value, $V_r\sqrt{2}$, of rated no-load transformer output voltage per anode plotted against the ratio of the direct current I to rated direct current I_r for percentage commutating reactance $X_c' = 10\%$.

(3) EFFECT OF THE 100c/s RIPPLE ON THE MOTOR

The 100c/s ripple component in the rectifier output voltage drives an alternating current which is limited by the total inductance of the d.c. circuit. For $X_c' = 10\%$ commutating reactance and rated load, the peak 100c/s current is approximately

$$I_{100} = \frac{0 \cdot 84 V_d}{2\pi \times 100 \times \Sigma L} \quad . \quad . \quad . \quad . \quad (12)$$

where V_d is the direct voltage; the factor 0·84 is obtained from Section 2.6.1 and Fig. 7; ΣL is the total inductance in the d.c. circuit.

Without special precautions this current would flow through the main field winding. The oscillating main-field produces a short-circuit current in the armature coils which undergo commutation. On a single-phase commutator traction motor the brush spans two commutator bars or slightly more, the transformer voltage is kept below 3 volts per commutator bar and the quadrature component of the compole field is specially arranged to compensate the transformer voltage. On the d.c. traction motor the peak commutator bar voltage at no load under the centre of the main pole is of the order of 20 volts. The r.m.s. voltage is therefore 14 volts, and is produced by the full flux at the armature frequency of, perhaps, 50c/s. The brush spans between three and four commutator bars. The heel-to-toe transformer voltage produced by the full main pole flux at 100c/s would therefore be

$$14 \times 4 \times \frac{100}{50} = 112 \text{ volts (r.m.s.)}$$

If the uncompensated transformer voltage is 1 volt per commutator bar or 4 volts per brush—which is already very high—the peak a.c. flux must be limited to 4/112 (= 3·6%) of the d.c. flux. Tests on the experimental motor with similar constants have shown that a main flux ripple of even 2·25% peak has a bad effect on commutation. It is therefore necessary to keep the main flux steady and to prevent practically any oscillation. Another requirement is that the compole flux should follow reasonably well the oscillation of the motor current.

There are two ways of stabilizing the main flux—either by means of a damper winding or by a resistive diverter to the main field winding. The solid yoke of the motor forms such a damper winding, which suffers, however, from a large leakage to the main pole winding, so that a resistive diverter to the main field winding is necessary. A shunt for 15% direct current, i.e. with five to six times the resistance of the field winding, is sufficient to by-pass about 75% of the 100c/s alternating current. This follows from the fact that already the 100c/s reactance of the leakage field of the main field winding which misses the solid yoke is 20–30 times greater than the resistance (see Section 5.1).

The 100c/s reactance of the main field winding is virtually short-circuited in this way, and the inductance of the motor is in the armature and compole winding only.

(3.1) Inductance of Armature and Compole Winding

The armature inductance is produced to a very great extent by the cross flux under the main poles and by the leakage flux in the slots and round the end windings. The leakage between armature and compole is very great—of the order of 90%—so that the common field which traverses the air-gap is small. The inductance of the compole winding is therefore mainly due to its leakage field. The result is that the armature voltage and compole voltage are additive if an alternating voltage is applied to both in series, although they are wound in opposition. In general, it can be stated that the compole voltage is about 25–50% of the armature voltage.

The question now arises as to the effect of a 100c/s ripple voltage on the motor. Without a smoothing choke a ripple voltage having a peak value of about 84% of the direct voltage (for $X_c' = 10$ and at the rated output) appears at the terminals of the motor. As a first approximation it can be assumed that this voltage has to be balanced by the cross-flux under the main poles. If the main pole has a uniform air-gap the current in the armature winding produces the flux density shown in Fig. 10 on the straight line DOE. The flux interlinked with each armature coil follows the parabola ABC. This is also the distribution of the alternating voltage on the commutator under the main pole.

Two time instants are considered as follows:

(*a*) *The instantaneous ripple voltage is at its maximum.*—The alternating current and the a.c. cross-flux are zero. Approximately two-thirds of the ripple voltage have to be balanced by the parabolic voltage distribution under the main pole, the remainder being dropped on the compole winding. The average voltage between commutator bars is

$$\frac{2/3\,V_{100m}}{N_c/2p \times \beta}$$

where V_{100m} = Peak 100c/s ripple voltage on the terminals of the motor.
$N_c/2p$ = Number of commutator bars per pole.
β = Ratio of pole arc to pole pitch.

The maximum value under the centre of the main pole is 1·5 times higher and is

$$\frac{V_{100m}}{N_c/2p \times \beta}$$

This parabolic voltage distribution has to be added to the direct voltage produced by the steady main flux and the direct armature current.

The air-gap is usually graded and the maximum value of the alternating-voltage distribution under the main pole is more than 1·5 times the average value. The peak 100c/s ripple voltage on the motor terminals without smoothing choke is of the order of 84% of the direct voltage. The no-load component of the commutator-bar voltage is therefore almost doubled by the a.c. component.

(*b*) *The instantaneous ripple voltage is zero.*—The alternating current and the a.c. flux have peak values.

The no-load component of the commutator bar voltage consists of the d.c. component only. The armature reaction is increased by the peak value of the ripple current (straight line DOE, in Fig. 10).

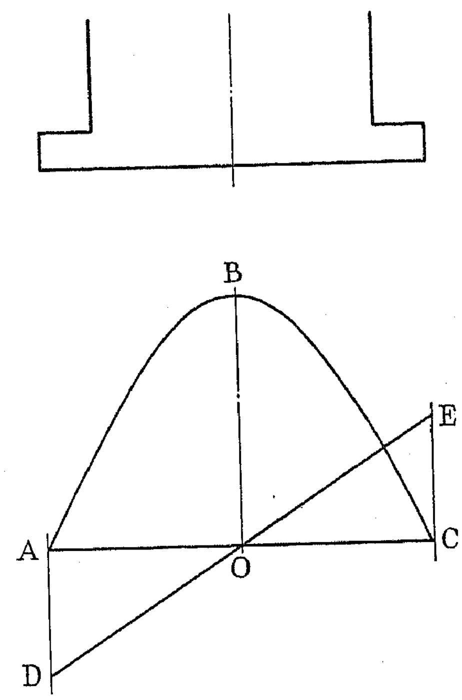

Fig. 10.—Voltage distribution in armature winding owing to ripple current.

ABC: Ripple voltage has peak value, ripple current is zero.
D–O–E: Ripple voltage is zero, ripple current has peak value.

Without smoothing, the peak value of the ripple current bears a similar relation to the rated direct current as the peak value of the ripple voltage does to the direct voltage. This means that the load component of the commutator bar voltage is nearly doubled.

Saturation in the armature teeth and in the pole shoes complicates the picture considerably, but in general it can be stated that, without smoothing, the no-load and the load component of the commutator-bar voltage are doubled, but not simultaneously.

It is inadvisable to design the motor with a high armature-circuit inductance in order to reduce the ripple current and to save on smoothing inductance. The inductance of the motor could be increased by reducing the main pole air-gap and by increasing the number of armature conductors. This results in an unusually small ratio of field to armature turns and in high stray energy losses in the pole shoe.

The additional no-load component of the commutator-bar voltage at the instant (*a*) and the additional load component at the instant (*b*) remain nearly the same unless the number of commutator bars has been increased. The only gain would be a reduction in ripple current.

It can be stated quite generally that it is wrong to prejudice the design of the motor in this way. The required limitation of the ripple current should be obtained by a smoothing choke of sufficient inductance.

For 10% total commutating reactance the peak ripple voltage is, at the rated output, approximately 84% of the direct voltage. If, for instance, the ripple voltage is 24% at the motor terminals, the smoothing choke has to be designed for a 100c/s r.m.s. of $60/\sqrt{2}$% (= 42·4%) of the direct voltage and for the rated direct

current. The volt-ampere rating of the smoothing choke will then be approximately one-half of the rated d.c. output. This is considerable, and it can be understood that there is a tendency to limit the smoothing to the really necessary degree and to allow the ripple current to have the maximum value consistent with good performance.

(4) TESTS

The tests were carried out with a motor whose rated continuous input is 600 volts at 120 amp. The field winding is so arranged that full field (1 050 r.p.m.) is obtained with a resistive divert of 15% current, and weak field (1 820 r.p.m.) with a resistive divert of 67%. Two different motors of this type were tested. Both have fully laminated compoles and a solid yoke. However, one motor has, parallel to the solid yoke, a laminated ring of small radial depth which carries the 100 c/s component of the compole flux.

Two smoothing chokes were available which made it possible to increase the inductance of the d.c. circuit to twice and four times the motor inductance. A large number of oscillograms and many ballistic flux measurements were taken.

(4.1) 100 c/s Ripple in Main Flux, Motor Current and Compole Flux

A few typical oscillograms for 15% divert and two choke coils in series are reproduced in Figs. 11 at the continuous rating input of 600 volts 120 amp.

The peak main flux ripple is calculated from the ripple voltage measured with a search coil round the main pole tips. For full field (15% divert) and no choke coil, one and two choke coils in series, the peak values are 2·25, 1·43 and 0·78% of the d.c. flux, respectively. The main field is therefore sufficiently steady with 15% divert and with one or two choke coils in series.

The peak ripples in the motor current for the three cases of smoothing are 88, 44 and 22% respectively.

The peak ripple of the compole flux was measured on a search coil round the compole tips, and could be checked from the r.m.s. voltage measured on the compole winding. On the motor with laminated yoke ring, the 100 c/s oscillation of the compole flux corresponds exactly to the oscillation of the motor current. This is so even in the extreme case without smoothing choke and 88% peak ripple. On the motor without laminated yoke ring the 100 c/s peak compole flux corresponds approximately to only half the peak ripple current.

(4.2) Commutation

The most important test was the observation of the commutation. This was done visually, using a commutation chart which assigns eight different numbers to the various degrees of sparking. However, this is not an exact measurement. An attempt was therefore made to observe the commutation on a cathode-ray oscillograph by filtering out the low-frequency components of the voltage between positive and negative brushes and to measure the high-frequency components which are produced when the brushes spark. The filter circuit has, from a frequency of 10 kc/s upwards, a rapidly falling impedance. In order to gain more

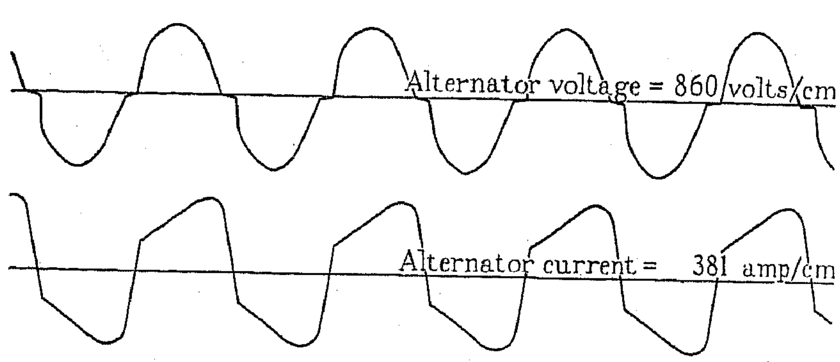

Fig. 11A.—Oscillogram of primary voltage and current supplied to transformer.
Motor field shunted 15%.
Two choke coils in series.

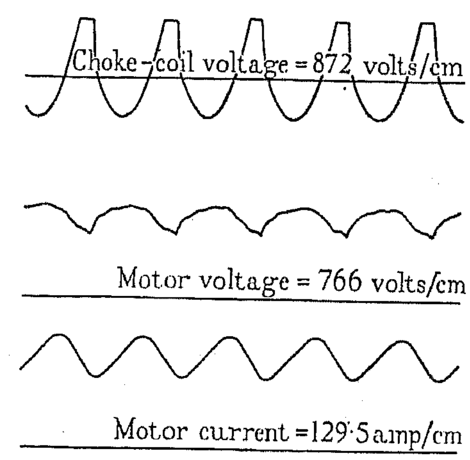

Fig. 11B.—Oscillogram of choke-coil voltage, motor voltage and motor current.
Motor field shunted 15%.
Two choke coils in series.

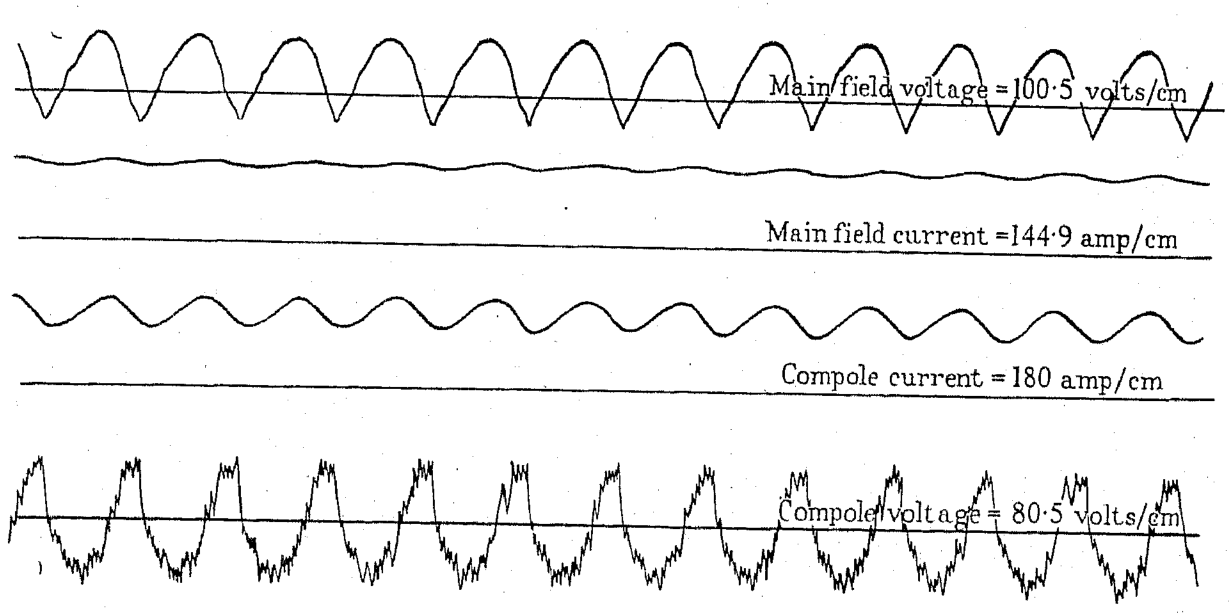

Fig. 11C.—Oscillogram of main field voltage and current, and compole voltage and current.
Motor field shunted 15%.
Two choke coils in series.

confidence in the use of the cathode-ray oscillograph for commutation tests, a point of the black-band curve taken with an ordinary d.c. supply was checked on the cathode-ray oscillograph at 600 volts 120 amp (full field and weak field). The compole excitation was boosted and diverted up to 25 amp in steps of 5 amp and the commutation number of the visual observation and the voltage on the cathode-ray oscillograph were recorded. They are plotted against compole excitation in Fig. 12. The

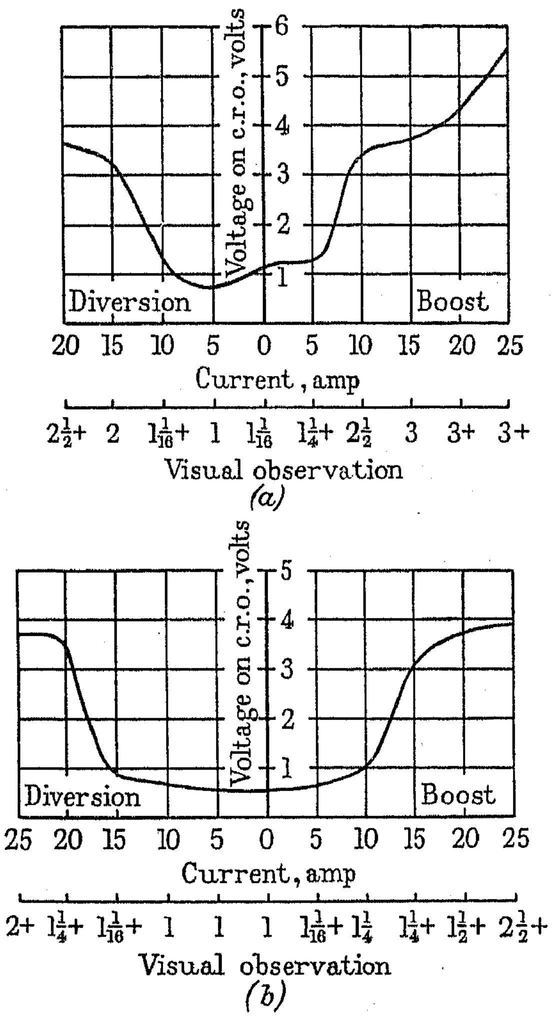

Fig. 12.—Black-band test on motor at weak field (*a*) and full field (*b*) with direct-voltage supply of 600 volts 120 amp.

Compole excitation boosted and diverted by 5, 10, 15, 20 and 25 amp. Visual observation of commutation and voltage on cathode-ray oscillograph recorded simultaneously.

agreement between both series of observations is remarkably good.

The black-band curve cannot be taken with supply from the rectifier because a resistive divert or a booster parallel to the compole winding diverts, to a great extent, the 100 c/s ripple current. The correct method would be to use an inductive divert or boost so adjusted that the ratio of the peak ripple to the d.c. component remained the same. This is obviously very difficult.

The commutation tests on the cathode-ray oscillograph give results which are consistent throughout and give much more discrimination than the visual observations, which, however, they confirm and amplify. The motor with laminated yoke ring is better than the motor with solid yoke, particularly at weak field (high speed) and at a low degree of smoothing (one choke in series, 44% current ripple). The motor with laminated yoke ring makes it possible to provide less smoothing, which not only reduces the size, weight and price of the smoothing apparatus but has advantages in other respects.

A typical set of readings on the cathode-ray oscillograph of the output voltage from the high-pass filter for the motor at weak field, with and without a laminated yoke ring (for the latter motor the figures are in brackets) is given in Table 1.

Table 1

COMMUTATOR VOLTAGE MEASURED BY CATHODE-RAY OSCILLOGRAPH

Choke coils in series	Motor terminal voltage		
	400 volts	500 volts	600 volts
	Brush sparking voltage.		
	volts	volts	volts
2	1·05 (0·99)	1·26 (1·20)	1·65 (1·59)
1	1·74 (2·6)	2·10 (3·50)	2·9 (4·2)
none	4·2 (7·8)	5 (9·3)	5·6 (11·4)

The laminated yoke ring is a complication which will be avoided whenever possible. The following consideration will help to decide this question. For a motor current I and a peak ripple current I_{100} the extreme values are $I + I_{100}$ and $I - I_{100}$. For the motor without laminated yoke ring the compole field corresponds to a current of approximately $I + I_{100}/2$ and $I - I_{100}/2$. It should therefore be possible during the black-band test:

(*a*) To divert the compole winding at the point $I + I_{100}$ until the resultant ampere-turns of compole and armature correspond to a current of $I + I_{100}/2$ for the motor without divert on the compole winding.

(*b*) To boost the compole winding at the point $I - I_{100}$ until the resultant ampere-turns correspond to a current of $I - I_{100}/2$.

The speed in (*a*) and (*b*) should correspond to the current I and not to $I + I_{100}$ or $I - I_{100}$. This has to be obtained during the test by regulating the supply voltage.

Both points should either be inside the black-band zone or should be obtained without injurious sparking.

It is shown in Section 5.2 that the divert in (*a*) is

$$x = 100 \times \frac{\alpha - 1}{2\alpha} \times \frac{\rho}{1 + \rho}\% \quad . \quad . \quad . \quad (13)$$

and the boost in case (*b*) is

$$y = 100 \times \frac{\alpha - 1}{2\alpha} \times \frac{\rho}{1 - \rho}\% \quad . \quad . \quad . \quad (14)$$

α is the ratio of compole to armature turns and $\rho = I_{100}/I$.

Table 2

BOOST AND DIVERT REQUIRED ON D.C. BLACK-BAND CURVE FOR SATISFACTORY COMMUTATION OF MOTOR WITH UNLAMINATED FRAME

ρ	Divert x	Boost y
%	%	%
22	2·58	4·03
44	4·36	11·25
66	5·68	27·8
88	6·69	105

Table 2 shows the black-band requirements for $\alpha = 1 \cdot 4$ and a series of values of ρ.

The black-band curve at constant speed, corresponding to the current I for 44 and 22% ripple current—assuming it is symmetrical for boosting and diverting—must pass through the

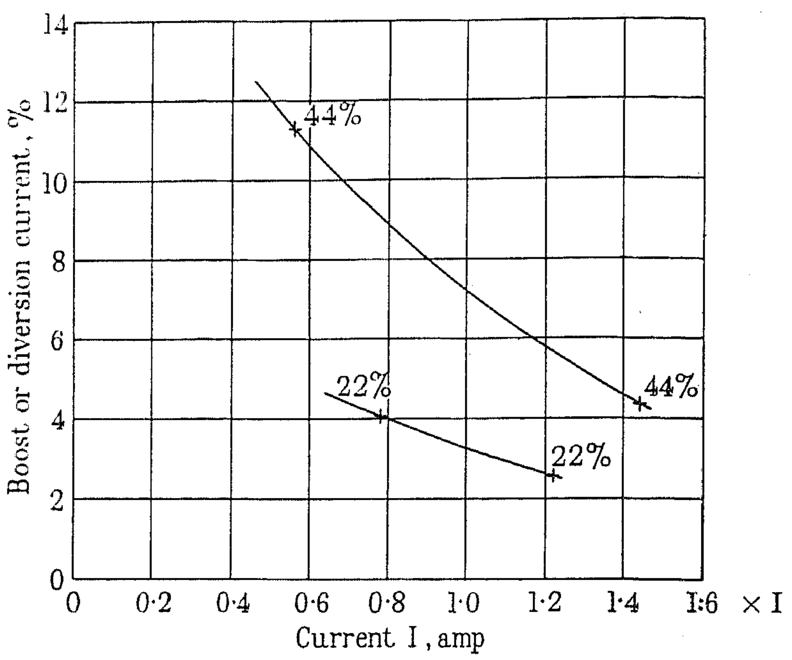

Fig. 13.—Motor with solid yoke.

Ratio of compole to armature turns $N_p/N_a=1\cdot4$.
Black-band curve with direct current as required for good commutation for motor with 22 and 44% ripple current.

points marked 44 and 22% in Fig. 13. It is obvious from this diagram that the improvement in commutation for the motor without laminated yoke ring is very great if, by means of more smoothing, the ripple current is reduced from 44 to 22% (two choke coils in series instead of one). This is confirmed by the commutation tests recorded on the cathode-ray oscillograph (see Table 1). The readings in brackets for the motor without laminated yoke are nearly three times higher for one choke coil in series instead of two.

(4.3) Losses and Temperature Rise

Comparative temperature tests with the pulsating supply from the rectifier and with normal d.c. supply gave, for 44% current ripple, a 7–8% higher temperature rise on the armature winding. The calculated losses of the ripple current—including eddy-current losses at 100c/s—are, for the whole armature winding, 12·5% of the genuine resistive losses of the direct current. The ripple current in the compole winding produces a 100c/s stray field which can give rise to high eddy-current losses if the conductors in the coils are arranged in the wrong way.

(4.4) Distortion of the Alternating Line Current

The distortion of the alternating line current, i.e. from the alternator into the transformer, was studied by taking oscillograms and also by using a harmonic analyser. It can be expected that the alternating current into the transformer and rectifier follows approximately the shape of the rectified current. The alternating current would have rectangular shape for complete smoothing.

The oscillograms of Figs. 11A and 14(*a*) and 14(*b*) give a comparison of the alternator current (line current) at 600 volts 120amp and full field (15% divert) for smoothing with two choke coils, one choke coil and without smoothing, respectively. It can be clearly seen that the alternating current assumes more closely the shape of a sine wave when the smoothing is reduced.

All harmonics including the ninth were recorded. They are reduced to about two-thirds if only one smoothing choke coil is used instead of two, and the ripple current is thereby increased from 22 to 44%.

For a constant motor current of 120amp at 600 volts and full field (15% divert) the harmonics in the current from the alternator into the transformer are shown in Table 3.

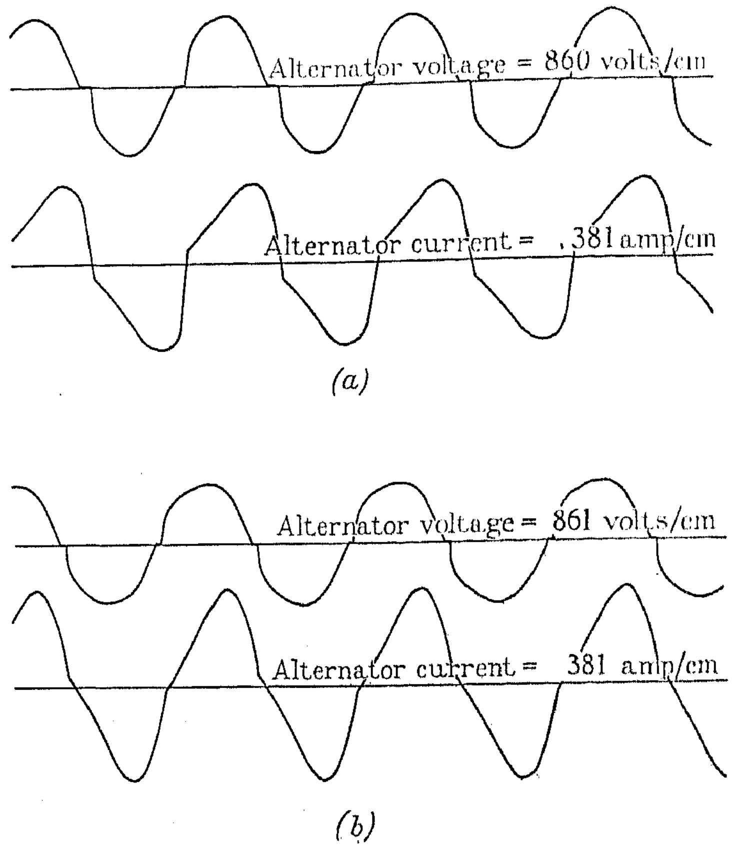

Fig. 14.—Oscillograms of primary voltage and current supplied to transformer. Motor field shunted 15%.

(*a*) One choke coil in series.
(*b*) No choke coil in series.

Table 3

ANALYSIS OF ALTERNATING-LINE-CURRENT DISTORTION

Choke coils in series	R.M.S. current	R.M.S. harmonic current				
		1st	3rd	5th	7th	9th
	amp	amp	amp	amp	amp	amp
2	221	213·7	51·3	25·2	13·8	9·9
1	232	228	39·3	18·6	10·2	6·3
none	255	252·4	35·4	10·2	5·4	4·1

(4.5) Transient Stability

The transient stability was tested in two ways—by the interruption and short-circuit tests.

(4.5.1) Interruption Test.

The motor was supplied at 600 volts 120amp, and the a.c. supply to the transformer was interrupted for about 1sec. Comparable tests carried out with direct current show that the peak currents are the same as in the a.c. tests, the ripple current during the latter tests being included. The transient stability is reduced considerably if the main field winding is shunted by a resistance. The peak motor currents—including the ripple currents—after remake are, at no divert, 15% and at 67% divert, 160, 350 and 540amp, while the peak main field currents are 160, 140 and 45amp. In general, remake is easier for the motor with rectifier supply because of the inductance in the a.c. circuit and the smoothing chokes which retard the rise of the motor voltage and current. Fig. 15 shows a typical oscillogram for full field (15% divert) and smoothing with one choke coil.

If field weakening is used for obtaining high speeds, every case should be examined to find whether field weakening above 15% should not be obtained by field tappings or by inductive shunting.

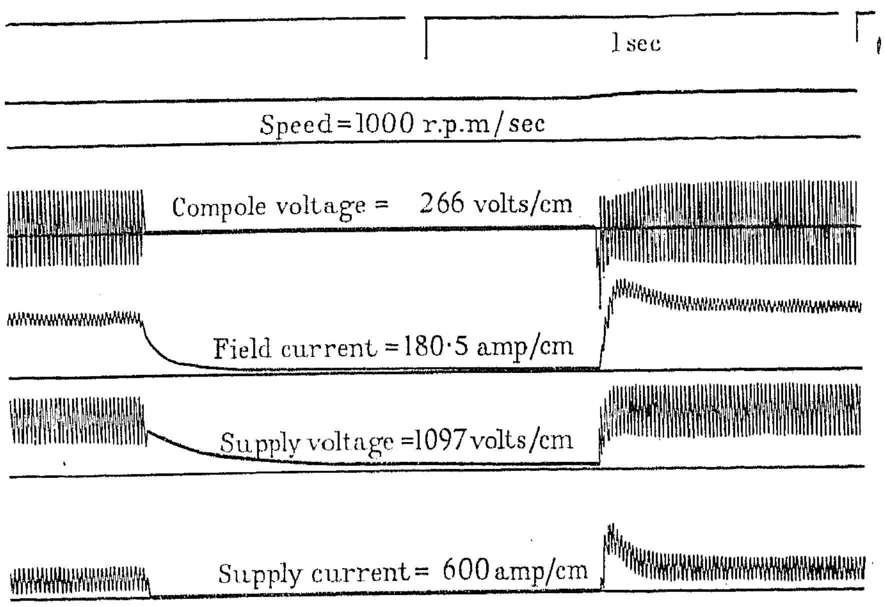

Fig. 15.—Oscillogram of interruption test. A.C. supply to transformer interrupted. Motor on 600 volts 120 amp.
Motor field shunted 15%.
One choke coil in series.

(4.5.2) **Short-Circuit Tests.**

The traction motors are nearly short-circuited in the event of a backfire in the rectifier. For this reason it is important to examine the transient stability under short-circuit conditions. The motor was supplied before the short-circuit at 600 volts 120 amp. Table 4 shows the results of a few short-circuit oscillograms.

Table 4

SHORT-CIRCUIT TESTS

Motor terminal voltage	Main field divert	Smoothing choke	Initial decrease of motor current	Peak motor current	Peak field current.
volts	%		amp/sec $\times 10^3$	amp	amp
600	None	None	28·6	−60	−60
600	15	None	53·2	−256	−38
500*	67	None	56·4	−732	+58
600	67	2	15·3	−624	+42
600	None†	None	45·2	−144	−144

* Limited by flashover.
† 67% field weakening by tapping on field winding.

The first three tests are carried out without smoothing chokes. The motor current reverses and reaches a peak of 60 amp without divert and 256 amp with 15% divert. At 67% divert the short-circuit current at 500 volts comes near the flashover limit at a peak motor current of 732 amp. With two smoothing chokes in series the motor can be short-circuited at 600 volts without difficulty. Under these conditions the peak motor current is 624 amp. The initial decrease of the motor current has been retarded to approximately one-quarter. The field current at 67% divert not only continues to flow in the motoring direction but even increases and tends to counteract the field-weakening effect of the heavy armature reaction. If field weakening of 67% is obtained by a tapping on the field winding, the peak motor current is only 144 amp at 600 volts.

The short-circuit tests confirm the conclusions drawn from the interruption tests for field weakening above 15% for high speeds.

(5) ACKNOWLEDGMENT

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(7) APPENDICES

(7.1) **Resistive Divert associated with Main Field Winding**

The e.m.f. of a d.c. motor is given by

$$V_m = 4\Phi f_a N_a 10^{-8} \qquad (15)$$

where Φ = Flux per pole.
f_a = Frequency of armature.
N_a = Number of armature turns per circuit.

$$\Phi = \frac{V_m \times 10^8}{4f_a \times N_a} \qquad (15a)$$

The leakage field of the main field winding is approximately $0{\cdot}2\Phi$. The inductance L_f of the main field winding, with current I_f and number of turns, N_f, owing to the leakage field, is

$$L_f = 0{\cdot}2\frac{V_m}{4f_a} \times \frac{10^8}{N_a} \times \frac{N_f}{I_f} \times 10^{-8} \qquad (16)$$

The 100 c/s reactance is

$$X_f = 2\pi \times 100 \times L_f \qquad (17)$$

$$= \frac{10\pi}{f_a} \times \frac{V_m}{I_f} \times \frac{N_f}{N_a} \qquad (17a)$$

The voltage drop in the resistance R_f of the main field winding is R'_f% of V_m

$$R_f = \frac{R'_f}{100}\frac{V_m}{I_f}$$

Thus

$$\frac{X_f}{R_f} = \frac{1\,000\pi}{f_a \times R'_f} \times \frac{N_f}{N_a}$$

If, for example, $f_a = 50$ (i.e. 1 500 r.p.m. for a four-pole motor),

$$N_f/N_a = 1$$
$$R'_f = 2 \text{ (2\% loss in main field)}$$
$$\frac{X_f}{R_f} = 31{\cdot}4$$

The 100 c/s reactance of the leakage field is then 31·4 times greater than the resistance.

A resistive divert of resistance R_d is connected to the field winding (see Fig. 16).

The motor current I has a 100 c/s component with peak value I_{100}. The 100 c/s component of the field current is I_{100f}.

$$I_{100f} = I_{100}\frac{R_d}{\sqrt{[(R_d + R_f)^2 + X_f^2]}}$$

for

$$X_f \gg R_d + R_f$$

$$I_{100f} \sim \frac{R_d}{X_f} \times I_{100}$$

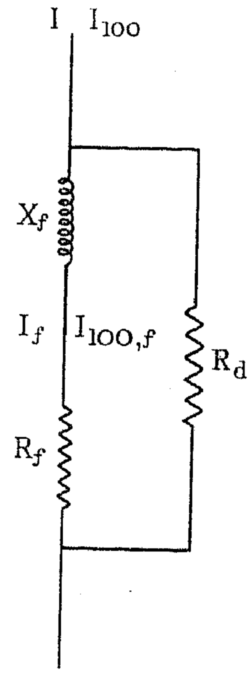

Fig. 16.—Resistive divert, R_d, to main field winding (100 cycle reactance X_f, resistance R_f, direct current I_f, peak ripple current $I_{100,f}$).
I = Motor direct current.
I_{100} = Peak ripple current.

For 15% divert, $R_d = 5{\cdot}67R_f$; and with $X_f = 30R_f$, $I_{100f} = 19\%$ of the 100c/s ripple component of the motor current. This means that, for instance, 40% ripple in the motor current is reduced to less than 7·6% in the field current. The ripple component of the field current will be smaller because of the additional reactance of the 100c/s main flux which has not been included in the above calculation.

(7.2) **Divert and Boost associated with Compole Winding**

(*a*) For the current $I + I_{100}$ the compole flux corresponds approximately to $I + I_{100}/2$ and is therefore too small. During a d.c. black-band test with the current $I + I_{100}$ the resultant excitation of the compole flux is reduced to $I + I_{100}/2$ by x% divert.

N_p = Number of compole turns.

$\alpha = N_p/N_a$ = Ratio of compole to armature turns.

$\rho = I_{100}/I$ = Ratio of peak ripple to d.c. current.

The ratio of the resultant ampere-turns with and without divert has to be $(I + I_{100}/2)/(I + I_{100})$ and therefore

$$\frac{IN_p\left(1 - \frac{x}{100}\right) - IN_a}{IN_p - IN_a} = \frac{I + \frac{I_{100}}{2}}{I + I_{100}}$$

and

$$x = \frac{\alpha - 1}{2\alpha} \times \frac{\rho}{1 + \rho} \times 100\% \quad . \quad . \quad . \quad (13)$$

(*b*) For the current $I - I_{100}$ the compole flux corresponds to $I - I_{100}/2$, and is therefore too great. During a d.c. black-band test with current $I - I_{100}$ the resultant excitation of the compole flux is increased to $I - I_{100}/2$ by y% boost.

The ratio of the resultant ampere-turns with and without boost has to be $(I - I_{100}/2)/(I - I_{100})$.

Therefore

$$\frac{IN_p\left(1 + \frac{y}{100}\right) - IN_a}{IN_p - IN_a} = \frac{I - \frac{I_{100}}{2}}{I - I_{100}}$$

and

$$y = \frac{\alpha - 1}{2\alpha} \times \frac{\rho}{1 - \rho} \times 100\% \quad . \quad . \quad . \quad (14)$$

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DISTORTION OF TURBO-ALTERNATOR ROTOR WINDINGS THROUGH THERMAL STRESS

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SUMMARY

The theory of copper shortening in turbo-alternator rotor windings is extended to take account of recent research on silver-free and silver-bearing coppers.

The interaction of the turns of a slot stack operating within the elastic strength of the material is analysed and the results are applied to determine the stress distribution in a large winding of cold-worked silver-bearing copper under various conditions of practical interest. Deformation rates at given temperatures are estimated for such a winding. The basis of evaluation of the stack interface friction coefficients applied in the estimate is indicated.

LIST OF PRINCIPAL SYMBOLS

Strips are numbered 1, 2 . . . m from top of slot.

a = Cross-sectional area of winding strip, in^2.

l_s = Half-length of coil side, in.

θ_0 = Temperature of rotor at routine starting up, °C.

θ_i = Operating temperature of rotor iron, °C.

θ_c = Operating temperature of turn considered, °C.

$e_1, e_2 \ldots e_m$ = Temperature strains in turns 1, 2 . . . m in portions locked relatively to rotor body, in/in.

$Ee_1, Ee_2 \ldots Ee_m$ = Stresses in strips 1, 2 . . . m corresponding to $e_1, e_2 \ldots e_m$, lb/in^2.

$\mu_{w,1}, \mu_{1,2} \ldots \mu_{m-1,m}$ = Frictional coefficients between slot wedge and top turn, turns 1 and 2, and so on.

μ_t = Frictional coefficient between turns in general.

$l_1, l_2 \ldots l_m$ = Distances from end of coil side to points where turn 1 ceases to slide on slot wedge, turn 2 ceases to slide on turn 1, etc., in.

$p_{1l1}, p_{1l2} \ldots$ etc. = Stresses in turn 1 at distances l_1, l_2 . . . etc., from end of coil side, lb/in^2.

$p_{2l1}, p_{2l2} \ldots$ etc. = Stresses in turn 2 at distances l_1, l_2 . . . etc., from end of coil side; and so on, lb/in^2.

$a\Sigma p_l$ = Sum of forces in designated group of turns, at a section l in from end of coil side, lb.

$F_1, F_2 \ldots F_m$ = Centrifugal forces per unit length of individual turns 1, 2 . . . m, lb/in.

ΣF = Sum of centrifugal forces per unit length of designated group of turns, reckoning from bottom of stack, lb/in.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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(1) INTRODUCTION

(1.1) Present Position

As a result of the trouble experienced through distortion of turbo-alternator rotor windings, various modifications in winding design have been made since the late 1930's with the object of reducing the temperature rise of the copper, and new conductor materials have been introduced to lower the rate of deformation under given operating conditions. 10% cold-worked 0·1% silver-bearing (c.w.s.b.) copper came into use for rotor windings in the early 1940's, but while it was known to be much superior to both tough-pitch* and oxygen-free high-conductivity coppers in respect of creep rates and resistance to softening at operating temperatures, there was then little information on which to determine the limiting conditions of its application. Much information has become available in the past few years on the properties of silver-free and silver-bearing coppers, and it is the object of the paper to extend the theory of winding deformation to take account of the new data and predict quantitatively the performance of rotor windings of c.w.s.b. copper under specified operating conditions.

The action of copper shortening is slowly cumulative, and the test of operating experience takes many years, particularly since the continued increase in maximum output capacity is reflected in the size of the rotor, to which the amount of winding deformation is related. In view of the influence of rotor size on overall machine dimensions it is desirable that rotor windings should operate at the highest current loading consistent with assurance of freedom from insulation trouble and from excessive deformation throughout the life of the machine. It is therefore important to ascertain whether, for the largest machines contemplated, existing standard temperature limits, based on insulation characteristics, require amendment by reason of their relation to winding deformation.

(1.2) Necessity for Formal Analysis of Stress System in Winding Stacks

As this paper progressed it became clear that a formal analysis of the interactions of the turns throughout a slot stack was necessary for the elucidation of several specific questions in connection with the mechanism of copper deformation. Some important published conclusions regarding the basis of stress imposition in the stack, and on the relative values of the coefficient of friction, μ, at different stack interfaces, appeared to warrant critical examination in view of their bearing on the calculation of turn stresses. The effects of temperature gradients in the stack were of special interest in this connection.

A method presented itself for an approximate evaluation of μ at the interfaces of a winding stack by applying the results of the analysis to data obtained from windings discarded as a result of deformation.

The results of the analysis and these derived values of μ were applied in calculations of stress distribution for the evaluation of

* Before c.w.s.b. copper was adopted for rotor windings, annealed tough-pitch copper was usually employed for this purpose.

creep deformation rates in a large rotor winding of c.w.s.b. copper under specified operating conditions.

(1.3) Importance of Local Temperatures

Owing to the marked increase in creep strain rates with increasing temperature and stress even within the range of operating practice, local high temperatures are even more significant than was indicated by the original theory of copper shortening. The measurement of overall average temperature rise leaves the hottest-turn temperatures a matter for estimation: the possibility of zone-temperature measurement, at any rate on prototype machines, is therefore suggested for the consideration of manufacturers.

(1.4) Purpose of Historical Review

A brief review of the history of rotor-winding distortion is included because the apparent nature of the problem has changed greatly since the original theory was formulated, and some linking up of its successive phases seems desirable at this stage.

(2) HISTORICAL REVIEW

(2.1) Basic Theory of Deformation

The basic theory of rotor winding deformation is well known, and here it will be dealt with only briefly. During the warming-up period the winding tends to expand relatively to the rotor body, since the winding is hotter than the rotor body and also has a higher expansion coefficient. The machine being on speed, the expansion of the slot turns is resisted by frictional restraint due to centrifugal pressure between the turns of the winding stack and between the top turn and the slot wedge.

The frictional forces acting on the end portions of the strips may, depending on the length, diameter and speed of the rotor, be sufficient entirely to prevent the expansion of the mid-length sections relative to the rotor body. If then the temperature strain in these locked mid-length sections is beyond the elastic limit of the copper, super-elastic deformation will occur.

When the machine is shut down and cools, the turns assume a new free length slightly less than their original length, frictional restraint being absent. The process is repeated at each operating cycle, and the cumulative shortening of the slot strips may be sufficient in the course of years to cause damage through distortion of the end turns.

Failures through rotor-winding distortion became widespread with more frequent two-shift operation in the 1930's, and with increasing unit capacities at 3 000 (or 3 600) r.p.m.

Some of the earliest recorded cases of rotor-winding distortion occurred in the Union of South Africa,* where early in 1936 the theory outlined above was there put forward for consideration by the manufacturers. It had been observed that distortion was most marked in the lower turns of the slot stacks, and it was suggested that this was due to the temperature being highest in that region. Later in the year the above theory of frictional restraint, arrived at independently in the United States, was outlined in a paper by Laffoon and Rose.[1]

(2.2) Early Measures for the Avoidance of Deformation

During the following years various measures for overcoming the trouble were tried, namely:

(*a*) Rigid packing of the corners of the end turns to resist shortening of the slot strips.

(*b*) Pre-cooling of the rotor at normal speed with the object of removing the compressive strain in the slot windings before shutting down.

(*c*) Pre-heating at low speed, as part of the starting-up routine, to bring about unresisted expansion of the copper.

(*d*) The use of hard copper windings.

(2.2.1) Rigid Packing of End Turns.

In the author's experience so-called rigid packing (i.e. continuous packing round the corners of the coils) has not been effective in preventing deformation. The large number of strips comprising a winding can exert a very large aggregate compressive force relative to the crushing strength of available insulating materials, and packing systems designed for rigidity have been found to undergo severe crushing and disintegration, as predicted by Laffoon and Rose, who also considered that continuous packing would impede ventilation.[1] There appears to be no general agreement on the effectiveness or otherwise of continuous packing; some designs employ little or no packing within several inches of the corners of the coils, while other assemblies are fully packed.

(2.2.2) Pre-Cooling.

Pre-cooling was soon abandoned because the temperature reduction obtained was very small, as must be the case with windings cooled only by conduction to the rotor iron; while the procedure was objectionable in regard to the operation of the turbine.

(2.2.3) Pre-Heating.

Pre-heating was tried in South Africa over a number of years, and the results showed that, as there practised, it had no worthwhile effect in reducing distortion. The conditions of its application were not ideal, since the pre-heating current had to be limited to avoid overheating of the solidly-coupled generator transformers at low frequencies; while at higher speeds it was necessary to guard against excessive voltage. On the other hand, pre-heating has been reported in the United States to have arrested the progress of deformation in several windings which had distorted under normal operating routine.[2,3]

In 1945 and 1946 applications of pre-heating in Great Britain were described by R. H. Coates and B. C. Pyle in important contributions to the study of rotor-winding deformation.[4,5] It then appeared that, in the absence of the limitations referred to above, pre-heating would have an important place, at any rate as an interim measure, in operating routine. However, it appears that pre-heating has not been adopted in Great Britain on any considerable scale or as a formal requirement of the operating authority, the view being that it is of doubtful advantage—bearing in mind the inconvenience of the procedure.

(2.2.4) Use of Partly-Hardened Copper.

The use of partly-hardened copper for rotor windings was suggested by Laffoon and Rose in 1936,[1] and was recommended by Juhlin in 1939.[6] In the state of knowledge at that time on the properties of copper the proposal appeared sound, and was adopted in a number of cases. It took no account of creep strain, however, which, at operating temperatures, in combination with the stresses resulting therefrom, was later found to be very marked in ordinary copper. Creep rates are lower in cold-worked than in soft copper, but at operating temperatures softening of ordinary copper of a hardness corresponding to an effective level of creep resistance is so rapid as to nullify this apparent advantage.[7]

In slot stacks of severely deformed windings recently discarded, the author made numerous hardness measurements as a con-

* On the Rand Undertaking of the Electricity Supply Commission of the Union of South Africa 26 complete rotor rewinds have been carried out on 20 000kW and 33 000kW, 3 000r.p.m. units, following failure through distortion. This represents a direct expenditure, at present costs, of about £150 000. In addition, a number of partial rewinds and minor repairs had previously been effected; other rewinds are pending.

venient indicator of elastic strength and of the occurrence of super-elastic strain. The hardness throughout corresponded to only about 3% cold work, at which figure appreciable re-softening could not have occurred;[7] there was, however, no indication that the deformation was accompanied by an increase in hardness, as would have been the case if the deformation were due in part to super-elastic strain. The stress corresponding to the maximum (i.e. mid-length) value of frictional restraint, calculated on what appears to be a reasonable value of μ, was in fact somewhat lower than the elastic strength of the copper. The deformation was evidently due to creep strain and not, in any discernible degree, to strain beyond the elastic limit.

(3) LATER DEVELOPMENTS

(3.1) Graded Windings

In 1945 the suggestion was put forward from South Africa that rotor windings be graded in thickness so that the current density would be lower than normal in those turns which had hitherto been most subject to deformation, and higher in the undeformed turns near the periphery. Three grades of thickness, with steps of 10%, were proposed. The total amount of heat generated for a given current in a winding graded in these steps is only about 0·7% greater than in a uniform winding employing the same amount of copper. Moreover, the additional heat would be generated near the periphery, where it is most readily dissipated. The proposal was adopted by one manufacturer; on the other hand Horsley[8] considered that the additional heat generated in a graded winding more than offset its possible advantage.

(3.2) Cold-Worked Silver-Bearing Copper

By about 1945, 10% cold-worked 0·1% silver-bearing copper had come into fairly wide use for rotor windings of large and medium-size machines. Its properties had not at that time been fully investigated on a quantitative basis, but it was known to be more resistant to softening under temperature than ordinary copper, and also less subject to creep action under stress and temperature. So far as the author is aware, no instances of winding failure due to copper shortening have occurred with this material, but there was clearly a need for systematic inquiry to determine the range of its suitability for use in rotor windings, especially in very large machines. In 1951 such a survey was undertaken in Great Britain, covering the properties of silver-free and silver-bearing coppers at various degrees of hardness and over a range of temperature, in respect of retention of hardness, creep rates at various stress intensities, electrical conductivity, yield strength, ultimate tensile strength, etc.

The relevant data set out in the report on the above investigation[7] have been applied in this paper.

(3.3) An Amended Theory of Stress in Rotor Windings

In 1946, in a valuable and suggestive paper, W. D. Horsley[8] put forward an amended theory in regard to the imposition of stress in slot windings. He concluded that the strain in the windings should be referred to the top turn and not to the rotor iron; i.e. that temperature gradient is the criterion of stress, and not temperature difference relative to the rotor body. Horsley based his contention on the virtual absence of deformation in the top turns of windings in which other turns had undergone severe deformation. His view of the interaction of the turns was that the friction coefficient between the slot wedge and the top turn is comparatively small owing to varnish migration from the inter-turn insulation to the top of the stack, with the result that the rotor body exercises little frictional restraint on the stack.

In view of its implications, Horsley's theory is discussed in a later Section, following an analysis of the system of forces in a winding stack and the application of the analysis in the derivation of μ from evidence adduced from discarded windings.

Horsley considered that modern operating requirements could safely be met in windings up to the largest contemplated sizes, without reducing the standard limit of average temperature rise, by the use of c.w.s.b. copper in conjunction with a lowering of the temperature gradient achieved by reducing the total amount of inter-turn insulation: this being brought about by using a smaller number of copper strips, of increased cross-section, as compared with previous practice.

(3.4) Recent Developments in Rotor-Winding Practice

A number of recent developments are intended to reduce the temperature rise and gradient for a given current loading. They include direct hydrogen cooling through hollow conductors[9] or through radial ducts formed by registering slots in the strips; and the enclosure of groups of turns in copper sheaths to improve heat conductivity to the rotor teeth.[10] New materials with low creep rates have been developed, including an aluminium-base iron-manganese alloy.

It is stated that by reason of the relatively high resistivity of the aluminium alloy, the overall frame diameter for a given output is greater with rotor windings of this material than with copper: in consequence, for the largest units the use of the alloy involves the adoption of an armature construction with an outer frame in sections for separate shipment to meet railroad limitations.[11]

(4) CONDITIONS OF STRESS ANALYSIS IN SLOT STACK

The analysis is set out in the Appendix (Section 15).

For the range of operating conditions of practical interest the expansion stresses in the slot strips of rotor windings of 10% cold-worked 0·1% silver-bearing copper are well within the elastic strength of the material.[7]

In the analysis it is necessary to postulate the directions of the temperature gradients across the slot stack. In rotor windings of conventional design the indications are that the temperature rises from the top turn to some point near the bottom of the stack, with a fall from that point to the bottom turn. This is the condition considered in case (i) of the analysis. The simple case of uniform temperature across the stack is also included since this condition may be approached with direct cooling.

In view of the interest attaching to top-turn elongation sometimes observed in deformed windings, the relation $\mu_{w.1} < \mu_{1.2}$, which is a necessary condition for this action, is assumed in the analysis. The adjustment for μ = constant for all interfaces is obvious.

(5) EVALUATIONS OF μ IN ROTOR WINDINGS

(5.1) $\mu_{w.1}$ and μ_t for Soft-Copper Windings

In a stack of m turns, if sliding occurs along the interface of turns 9 and 10, for example, up to a distance l from the end, the sum of the forces at point l in all the turns below No. 9 is, in the absence of end-turn forces, equal to the aggregate friction force up to the point l of the interface of turns 9 and 10.

Thus,
$$\mu_{9.10} l \sum_m^{10} F = a \sum_m^{10} p_l \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\mu_{9.10} = \frac{a \sum_m^{10} p_l}{l \sum_m^{10} F} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If sliding occurs up to point l of the slot-wedge/top-turn interface,

$$\mu_{w.1} = \frac{a \sum_{m}^{1} p_l}{l \sum_{m}^{1} F} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If the stress in a single turn (No. 9, say) at a distance l from the end is known, and the upper and the lower faces of the turn slide up to point l, then μ for this turn is given by

$$ap_{9l} = \mu_{8.9} l \sum_{m}^{9} F - \mu_{9.10} l \sum_{m}^{10} F \quad . \quad . \quad . \quad (4)$$

Putting $\mu_{8.9} = \mu_{9.10} = \mu_t$, since the values should be virtually equal for all except the top few interfaces in any case,

$$ap_{9.l} = \mu_t l \left(\sum_{m}^{9} F - \sum_{m}^{10} F \right) = \mu_t l F_9 \quad . \quad . \quad . \quad (5)$$

$$\mu_t = \frac{ap_{9l}}{lF_9} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The analysis of Section 15, applied to the operating conditions of the particular case, shows the relations between the starting points of sliding of the turn interfaces for given conditions, and is valid for those sections of soft-copper windings operating within the elastic limit of the material. For example, when $\mu_{w.1} < \mu_{1.2}$ to the extent that $\mu_{w.1} \sum_{m}^{1} F < \mu_{1.2} \sum_{m}^{2} F$ and the temperature increases down the upper section of the stack, inter-turn sliding of the few turns immediately below the top turn is shown to take place only over the short end-portions, l_2, l_3, etc. Similarly, if the temperature decreases down the bottom section, the bottom turns slide on each other and on the hottest turn (and in some cases on one or more turns above it) only at their extreme ends. In the intermediate turns inter-turn sliding is maintained up to the points where locking relative to the slot wedge begins; that is, up to the starting-points of super-elastic deformation, if such should occur.

Strip stresses attained in service can be assessed approximately for certain points of windings discarded through deformation, provided the deformation is due in part to strain beyond the elastic limit, as shown by hardening of the material so affected, for the elastic strength of the material has been reached at such points. Where sliding is known to occur at these interfaces μ can be evaluated. Fig. 1 shows deformation and hardness curves for a slot strip of a discarded 25-turn rotor-winding coil of a 40 MVA generator. Many of the turns of this winding had evidently undergone both creep strain and super-elastic strain.

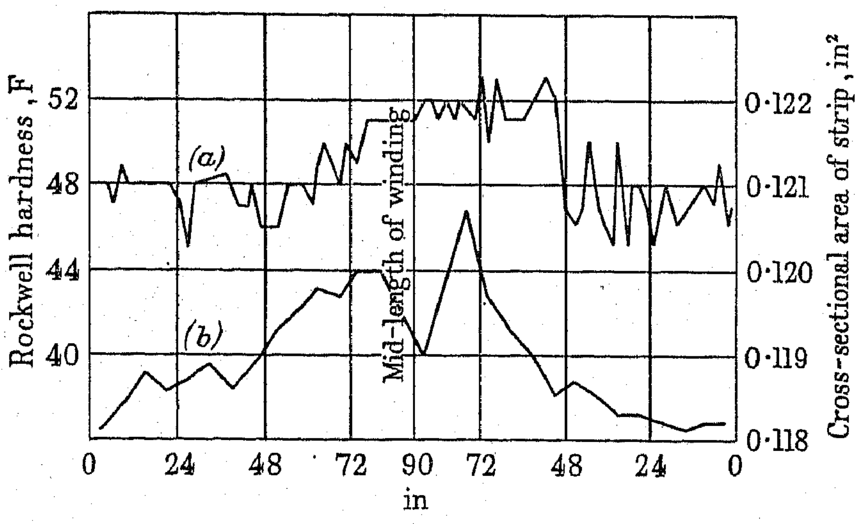

Fig. 1.—Typical hardness and deformation variations in slot strip of discarded winding.

(a) Hardness.
(b) Area.

It is to be noted that the hardness has a constant value from the ends of the strip to points l near mid-length, where the elastic limit has been reached, and thereafter rises towards mid-length. If the temperature strain is sufficient, the hardness will increase right up to mid-length and the limit of sliding will advance to that point. However, the increase in hardness is small, as noted by Horsley; it is not proportionate to the added available frictional restraint with increasing distance from the end of the strip (see final paragraph of this Section). Eqns. (1) to (6) cannot therefore be applied at points nearer mid-length than the starting-points of increased hardness.

In the top four turns of the stack examined there was no indication of any regular increase or decrease in sectional area. Thereafter there was increasing deformation by compression in successive turns down to turn No. 21, with a slight falling off from that point to the bottom turn. No regular increase in hardening could be detected in the top seven turns, but from turn No. 8 onwards an increase was evident at points varying somewhat round the average distance of 51 in from the ends. (Theoretically, these points should be progressively nearer the ends in the upper turns owing to increases in F, but the casual variations in hardness mask the small differences.) The average hardness figure up to the points of increase was 48 Rockwell "F," with a corresponding figure of 9 900 lb/in² for 0·1% proof stress. Tests showed that the tensile figure did not change significantly with small variations from this reference point of 0·1% proof stress. It is assumed that the figures for proof stress in compression would be approximately the same as in tension.

The strip dimensions are 0·8 in × 0·15 in, and the radii of rotation of the bottom and top strips respectively are 11 in and 15 in. Considering point $l = 51$ in at the interface of turns 13, 14, for example (these turns being in the group where sliding continues up to the point of super-elastic strain and therefore of hardening), the friction force exerted on turn 13 by group 25–14 is that due to 12 strips at a stress of 9 900 lb/in². For this winding $\sum_{25}^{14} F = 1\,390$ lb/in. With the above values eqn. (1) or (6) gives $\mu_{13.14} = 0{\cdot}20$.

Approximately the same result is obtained for the other interfaces in this region where the equation of sliding is known to be applicable.

In the case examined $\mu_{w.1}$ can be evaluated only between limits, because, in the absence of an indicative change in the condition of the top turn, the limit of sliding at the slot-wedge/top-turn interface cannot be determined. The assumption that sliding occurs up to point $l = 51$ in also at this interface yields the least possible value of $\mu_{w.1}$ for this winding. Taking p_{1l} as 0, and the increases in stress in successive strips at point l from turn No. 1 to turn No. 8 as being equal, the average stress at point l in turns Nos. 1–7 is 4 200 lb/in². The total expansion force exerted on the slot wedge by the stack at point $l = 51$ in is that due then to 18 strips at a stress of 9 900 lb/in² and 7 strips at an average stress of 4 200 lb/in². $\sum_{25}^{1} F = 3\,160$ lb/in. Applying the above values in eqn. (3), the minimum assignable value of $\mu_{w.1} = 0{\cdot}16$.

The result is not much affected by assuming for the top turn values of tension or compression consistent with slight deformation in that turn, since the consequent adjustment of the forces in the top few turns is small in comparison with the aggregate force in the turns stressed to the elastic limit.

Since the data for the above evaluations of μ_t and $\mu_{w.1}$ relate to the starting-points of increased hardness in the slot strips, the values are those applying at the first onset of super-elastic deformation. At that stage there was no cumulative shortening of the windings tending to produce tension in the strips through the resistance offered by the end packings to winding contraction. Also, it appears from observations during the withdrawal of rotor windings that there is no considerable friction between the windings and the sides of the slot cell. The derived values are therefore true friction coefficients.

With accumulating deformation, the tensile forces imposed on the strips by the end packings cause a progressive reduction in the net available force resisting expansion at given points. This reduction can account for the fact that the increase in hardness towards the mid-length points of the strips is small, as shown in Fig. 1 and already noted. This result cannot, at the low hardness figures in question, be ascribed in any considerable degree to re-softening.

(5.2) $\mu_{w.1}$ and μ_t for C.W.S.B. Copper Windings

In using the results of the previous Section to arrive at safe working values of μ_t and $\mu_{w.1}$ for large windings of c.w.s.b. copper, the following considerations arise: by the nature of rotor-winding construction μ is likely to vary considerably between different assemblies; in modern practice very sparing use is made of varnish as a binder for turn insulation; little account can be taken of the restraint exercised by the end packings on shortening action, since the acceptable limit of deformation is far less than that in the case examined; the effect of a given absolute amount of shortening in countering further deformation is in inverse ratio to the length of the rotor, and is also less in windings of c.w.s.b. copper than in ordinary copper by reason of the higher temperature stresses permissible in the former material.

The above factors suggest the choice of higher values of $\mu_{w.1}$ and μ_t for c.w.s.b. copper windings than those derived in the previous Section. It would seem that 0·25 is a fair working value of μ_t for large c.w.s.b. copper windings. On the same basis it appears that $\mu_{w.1}$ for such windings may be taken as not less than about 0·20, and may be as high as μ_t at 0·25. It is of interest to consider the differences in stress distribution for the two cases ($\mu_{w.1} = 0{\cdot}20$, $\mu_t = 0{\cdot}25$ and $\mu_{w.1} = \mu_t = 0{\cdot}25$) in windings of c.w.s.b. copper, since either condition appears possible. This is done in a later Section.

(6) BASIS OF STRESS CALCULATIONS IN ROTOR WINDINGS

In the previous Section it is shown that the observed deformation in rotor windings, taking into account elongation of the top turn when this occurs, requires that $\mu_{w.1}$ should not be much less than μ_t. In some cases it appears that $\mu_{w.1}$ may be equal to μ_t. If the restraint exerted on the winding stack by the slot wedge were in fact small, nearly all the turns operating below the average temperature of the stack would tend to lengthen and only those turns at above the average temperature would shorten, since the system of forces in the stack would be self-balancing (except for the influence of the end packings, which opposes shortening) if the restraint exerted by the slot wedge were absent.

It is to be noted that with $\mu_{w.1}$ anywhere near the value indicated by the present investigation, and with temperatures in the probable operating range, the mid-length Section of a long winding, even of c.w.s.b. copper, is wholly prevented from expanding relatively to the rotor body. Clearly, then, the stresses in the mid-length sections must be assessed on the basis of their temperature rise relative to the rotor body and not to the top-turn temperature.

To regard the top turn as reference implies that the stresses in a winding at uniform temperature are zero no matter how high the temperature may be relative to the rotor body. Since it appears practicable—with recent developments in direct cooling (possibly also with graded windings)—to approach uniformity of copper temperature, it is important that the correct criterion of stress be applied.

(7) STRESS DISTRIBUTION IN C.W.S.B. COPPER WINDING

The rotor-winding dimensions (Table 1) used in the numerical calculations of turn stresses were supplied by Mr. W. D. Horsley, and relate to a projected machine of about 200 MW capacity.

Table 1

ROTOR WINDING DATA

Turn No. (from top)	θ_c	Ee	F	ΣF	$\mu\Sigma F$
	°C	lb/in²	lb/in	lb/in	lb/in
1	86	4 300	452	5 245	1 049 (*a*) 1 311 (*b*)
2	96	7 000	444	4 793	1 198
3	105	9 400	436	4 349	1 087
4	112	11 300	428	3 913	978
5	121	13 800	420	3 485	871
6	126	15 200	412	3 065	766
7	131	16 500	403	2 653	663
8	136	17 900	395	2 250	562
9	139	18 700	387	1 855	464
10	140	19 000	379	1 468	367
11	139	18 700	371	1 089	272
12	136	17 900	363	718	180
13	134	17 300	355	355	89

l_s, 105 in. Speed, 3 000 r.p.m. Strip dimensions, 1·0 in* × 0·3 in.
Radius of rotation of bottom turn, 14·5 in.
Radius of rotation of top turn, 18·5 in.
$\mu_{w.1} = 0{\cdot}20$ [Condition (*a*)], $\mu_t = 0{\cdot}25$, $\theta_0 = 50$°C, $\theta_t = 80$°C.
$\mu_{w.1} = 0{\cdot}25$ [Condition (*b*)].

* Assumed for convenience in calculations.

This appears to be among the largest rotors for which a copper winding of conventional construction has so far been designed.

The winding has stacks of 13 turns, and the turn temperatures assumed in these calculations are listed in Table 1. They are taken from curve C of Fig. 6 of Horsley's paper,[8] showing the estimated temperature distribution in a rotor winding of normal construction at the date of that paper. The distribution is not necessarily representative of present practice, but the average temperature rise is within the limit of B.S. 225.

The temperature, θ_0, at routine starting up is taken as 50° C instead of the figure of 30° C adopted in Horsley's paper. The lower figure assumes that the machine has cooled to room temperature, while the higher figure, representing a less severe condition, appears from observations to be near the average for shut-down periods of varying duration in normal routine.

θ_i is taken as the average operating temperature down the tooth.

It is to be noted that if the stresses Ee of Table 1 were assessed by reference to the top turn, they would be less by the stress in that turn.

Fig. 2A shows the distribution of stress calculated by the method of the analysis of Section 15.1.2, for $\mu_{w.1} = 0{\cdot}20$, $\mu_t = 0{\cdot}25$, and Fig. 2B for $\mu_{w.1} = \mu_t = 0{\cdot}25$.

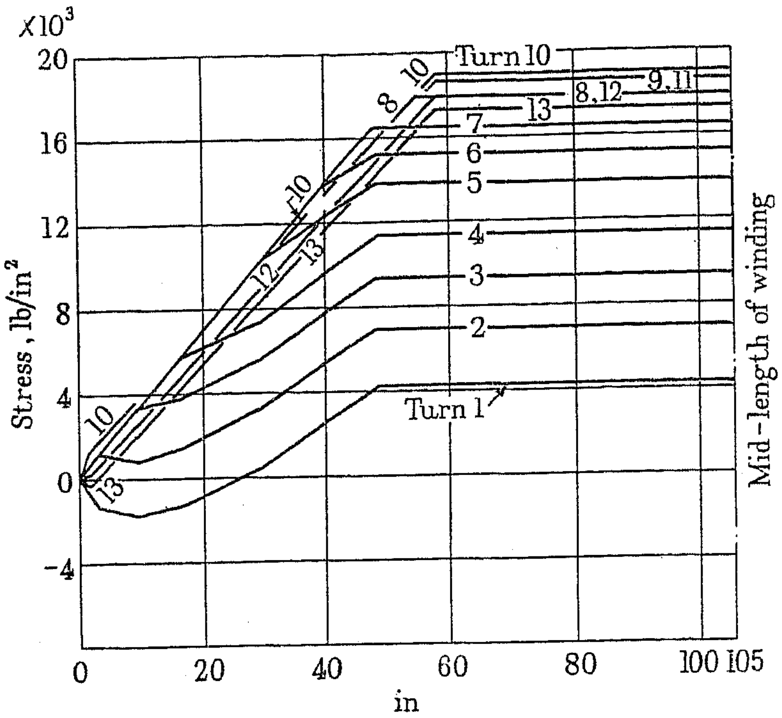

Fig. 2A.—Stress distribution in slot strips of 13-turn stack with temperature distribution of Table 1 when $\mu_{w.1} = 0{\cdot}20$, $\mu_{1.2}$, etc., $= 0{\cdot}25$.

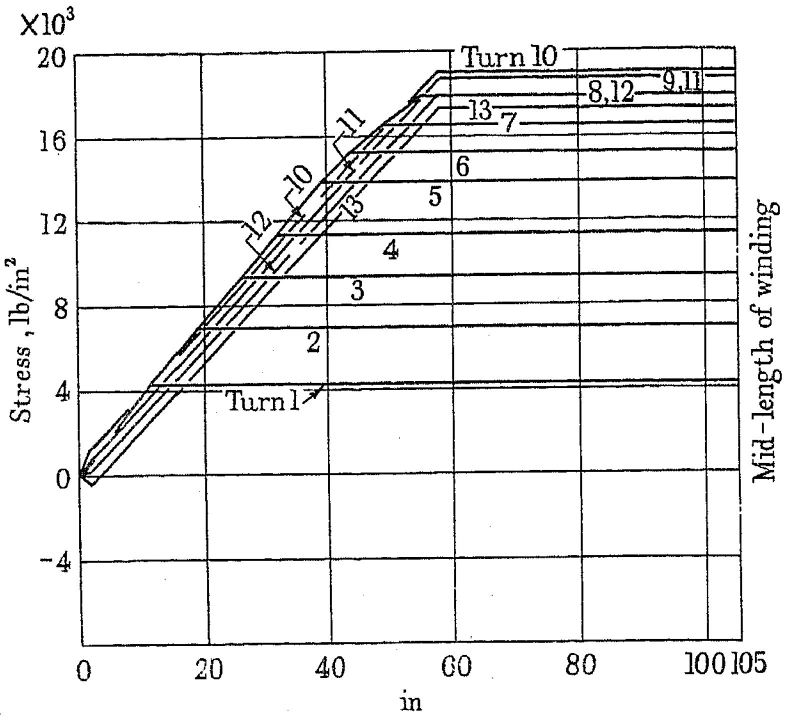

Fig. 2B.—Stress distribution in slot strips of 13-turn stack with temperature distribution of Table 1 when $\mu_{w.1} = \mu_{1.2}$, etc., $= 0{\cdot}25$.

(8) CONCLUSIONS FROM STRESS ANALYSIS

(8.1) Effect of Condition $\mu_{w.1} < \mu_{1.2}$ to the extent that

$$\mu_{w.1}\sum_{m}^{1} F < \mu_{1.2}\sum_{m}^{2} F$$

The maximum tensile stress in the end portions of the top turn when $\mu_{w.1} = 0{\cdot}20$, $\mu_t = 0{\cdot}25$ is negligible, as shown in Fig. 2A, for the assumed temperature distribution. The analysis shows that these tensile stresses increase with a steeper temperature gradient across the top turns; but this condition is unlikely to occur with modern cooling systems. The stress distribution in the hottest turn is the same for both the above relations of $\mu_{w.1}$ and μ_t when this turn is near the bottom of the stack, as in this case; but if the hottest turn were near the top its outer sections would be under lower stress for the lower value of $\mu_{w.1}$. The condition $\mu_{w.1} < \mu_t$, where present, evidently introduces no adverse factors, and can be left out of account, μ being taken as $0{\cdot}25$ for all interfaces.

(8.2) Effect of Falling Temperature Gradient down Stack

A falling temperature gradient towards the bottom of the stack is shown to result in an increase in stress in the expanding portions of the hottest turns, and an increase in the length of their mid-sections subject, in long rotors, to the full stress Ee. The effect is negligible with the temperature distribution so far assumed, where the hottest turn is near the botton of the stack and the temperature drop across the bottom turns is small. However, with cooling systems in which the cooling medium is admitted at the bottom of the stack and leaves at the top, the copper temperature will increase from the bottom to some point near the top. The temperature gradient will depend on the current loading relative to the cooling capacity, and its effect in highly-rated rotors may require consideration.

The temperature gradient assumed in the examination of this condition is shown in Table 2 and, for the sake of illustration, is steeper than is likely to occur in practice. The calculations of stress distribution are set out in Section 15.2. The results are given in the curves of Fig. 3, which show that the stresses in considerable portions of the hottest turn are substantially higher

Table 2

TURN TEMPERATURES AND MAXIMUM STRESSES IN ANALYSIS OF SECTION 15.2

Turn No.	θ_c	Ee
	°C	lb/in² × 10³
Top turn	99	8
2	111	11
3	118	13
4	125	15
5	133	17
6	140	19
7	133	17
8	125	15
9	118	13
10	111	11
11	103	9
12	96	7
Bottom turn	88	5

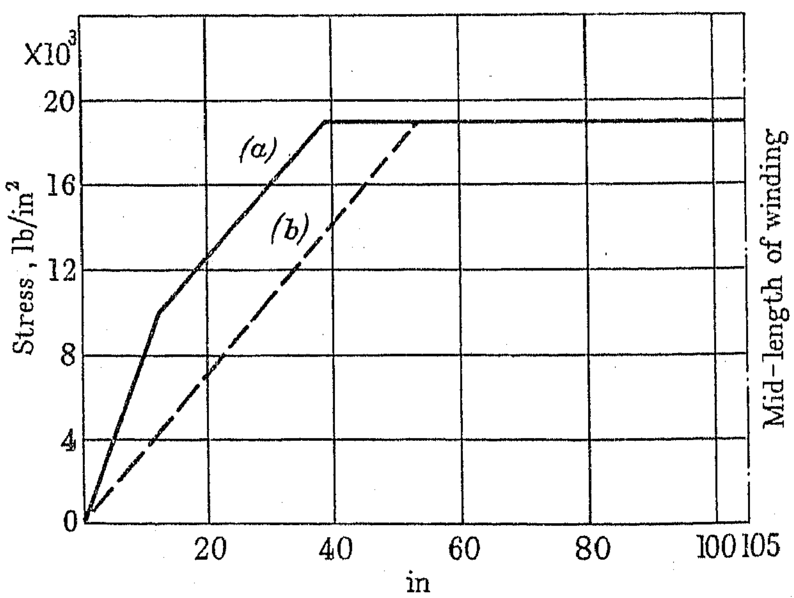

Fig. 3.—Stress distribution in slot strip No. 6 (down) of 13-turn stack.
(a) When No. 6 turn is at 140°C and temperature gradient falls steeply to bottom of stack (Table 2).
(b) When turns Nos. 6 to 13 are all at 140°C.

than would apply if all the turns were at the temperature of the hottest turn.

This effect is, of course, due to the fact that, with a temperature gradient falling towards the bottom turn, expansion of the hottest turns is resisted by frictional restraint on the lower as well as the upper face, as shown by the general analysis.

Where the above condition exists its effect may be more important in medium-size rotors than in very large units; for in the smaller winding only a short mid-section, or none, is subject to the full temperature stress *Ee*, and higher operating temperatures are therefore, in general, admissible in these cases. As shown by Fig. 3, however, the relative increase in stress due to the effect referred to is greater in medium-size windings than in very long ones, where the mid-length sections are unaffected.

It is clear from this example that where the temperature falls towards the bottom of the stack considerable error can result in calculations of stress distribution in the hottest turns on the simple assumption of sliding between turns up to the point of locking relative to the slot wedge. In these cases the method of the analysis must be applied in determining the stress distribution, although only one stage of this analysis is necessary, as shown in Section 15.2.

(9) ESTIMATES OF CREEP DEFORMATION IN LARGE WINDING OF C.W.S.B. COPPER

The stress distribution of Figs. 2A and 2B for the hottest turn of the rotor referred to in Table 1 is used as basis for the following estimates of creep strain in 100 000 hours of operation at 140°C.

(9.1) Initial Creep Strain under Intermittent Loading

Creep strain accruing in a winding strip during an on-load period results in relaxation of stress by an amount corresponding to the creep strain, until the original stress is reimposed in the next cycle. The rate of creep therefore diminishes as a result of relaxation, and the cumulative creep strain during the life of the machine is thus influenced by the duration of each load cycle. Initial creep rates are high at the start and fall off rapidly and then more slowly until the steady rate is reached. The initial creep phase, once passed, does not recur, but its completion period depends on the length of the operating cycle. If continuous-load periods of 130 hours (about a working week) during the early period of service are assumed, it appears from the creep data of Benson, McKeown and Mends's[7] paper that within the normal range of stress and temperature the initial creep phase, which would be completed in say 500 hours' continuous application of initial stress, will be reached in a few thousand hours of intermittent operation of the periods customary in practice. In the event of two-shift operation from the inception, the period of build-up of initial creep will be correspondingly shorter owing to the repeated earlier restoration of the initial stress, and will approximate to the time required under continuous application of the initial stress. In either case the time required for the completion of initial strain will be short in relation to the total life of the machine.

The operating stress in rotor windings is compressive, while cold working in normal manufacture is effected by drawing, which was shown to be equivalent to tensile overstrain. As compressive creep tests are inconvenient to apply, the creep measurements were made under tensile stress, and the relations between tensile creep rates were determined for silver-bearing copper cold worked by tensile and by compressive overstrain respectively. It was concluded that these relations would hold for the reverse case of operation under compressive stress of material cold worked in tension.[7]

The initial creep in specimens stressed at 14 000 lb/in^2 and 175°C in the reverse sense of the cold working strain was markedly in excess of the amount observed when the cold working and the test strain were in the same sense. Consideration of the test results has suggested a factor of three for the estimates of initial creep rates given below. The steady creep rate was the same for both conditions.

In the large winding here under consideration the initial stress in the locked section of the hottest turn is 19 000 lb/in^2 at 140°C, with a starting temperature of 50°C. The stress in the remainder of this turn varies almost uniformly from the above figure at the limit of the locked section to zero at the ends of the strip. The initial strain in the locked portion, allowing for the strain being in the reverse sense of the cold-work strain, is of the order of 0·4%, and in the remainder it averages about 0·1%. The lengths of the respective sections of the half-winding are 48 in and 57 in, and the initial creep in the half-winding thus amounts to about 0·25 in. Although this phase of creep strain occurs only once it is not negligible in its effects; for although part of the contraction may well be absorbed in harmless consolidation of the end packings, the winding system is likely to be left in a condition where any substantial degree of further contraction (due to steady creep) will have noticeable effects.

(9.2) Steady-Rate Creep Strain under Intermittent Loading

Steady creep rates are much lower than the initial creep rates, and the effect of relaxation due to steady creep is therefore comparatively small. The amount of relaxation which can occur in two-shift working is negligible, and it is necessary to examine its influence only in continuous working periods of, say, 130 hours. Under a constant stress of 19 000 lb/in^2 at 140°C the steady creep rate is about 0·01% in 1 000 hours, corresponding to a relaxation of 1 600 lb/in^2. The relaxation which occurs in a continuous running period of 130 hours, or even a considerably longer period, is thus negligible in the present connection. This is an interesting and important point of difference between the mechanisms of contraction through creep and through strain beyond the elastic limit respectively: in the latter case the action of deformation is immediate, and the frequency of starting and stopping is therefore a much more decisive factor than where creep rate is the sole criterion of deformation.

Benson, McKeown and Mends's[7] paper deals with the effects of intermittent creep and of creep recovery during the stress-free periods. By comparison of a test specimen under continuous load with another specimen under intermittent load at the same stress and temperature, it was shown that the effective creep rates are in the same ratio as the respective load periods, the effect of creep recovery during the off-load periods of the second specimen being nullified by its rapid creep in the early stage of the next loading cycle.

From this result, in conjunction with the fact that the effect of relaxation on load is negligible under the conditions here assumed, it is evident that steady-load creep rates can properly be applied over the aggregate time of a machine on load.

(9.3) Assessment of Steady-Rate Creep Values

The creep strain observations of Benson, McKeown and Mends[7] for various stresses and temperatures have been used in preparing the steady-creep curves of Fig. 4. An explanatory comment is necessary in this connection. While the durations of the tests covered by the tabulated observations of the above paper were adequate for the broad comparison of total creep amounts of silver-free and silver-bearing coppers over the stated periods, they were in some cases insufficient for the absolute assessment of steady-creep rates of 10% work-hardened 0·1% silver-bearing copper. Since the differences in creep rate due to

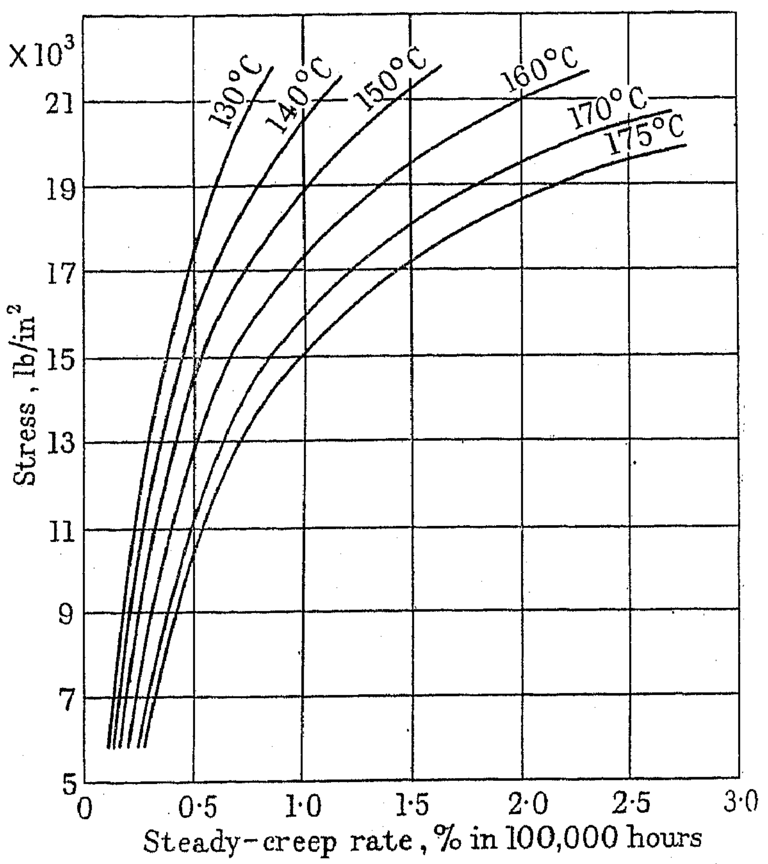

Fig. 4.—Steady-creep strain rates for 10–50% cold-worked 0·1% silver-bearing copper.

(Deduced from Benson, McKeown and Mends's paper.[7])

variations in hardness above 10% were shown to be small, the observations for all the hardness values (10%–50%) covered by the tests have been used in the present estimates without regard to the differences in hardness. Even then some omissions and inconsistencies remained in the derived steady-creep values, and the author has attempted to supply these deficiencies, so far as possible, from the information contained in the several creep curves relating to special tests included in the above paper. While, therefore, the curves here put forward are not to be taken as direct plottings of the tabulated observations, they should be reasonably indicative. Some inconsistencies in test results may be expected in view of the marked variations in creep behaviour noted in some metals and arising out of slight differences in their condition.

Notwithstanding the above difficulties in assigning steady-creep rates, predictions of creep behaviour of rotor windings still have value: creep strain has, indeed, become a specified criterion of performance in many connections, in some of which the same difficulty must apply. It seems desirable that there should be agreed curves of steady creep rates for c.w.s.b. copper of the quality and condition in present use, over the relevant range of temperature and stress. With such curves as a basis, the predicted behaviour of different designs of winding, or of the same design under different operating conditions, can be fairly compared.

(9.4) Steady-Rate Creep in Large C.W.S.B. Copper Winding (Table 1) in 100 000 Hours

The steady-rate creep in half the locked central section of the hottest turn (No. 10) for $\theta_c = 140°$C, $Ee = 19\,000$ lb/in², is 0·80% in 100 000 hours. The length of this portion is 48 in and the steady-rate creep amount is thus 0·38 in.

Since creep rate is not a linear function of stress, the strain rate for the sliding portion of the half-strip was determined by treating this portion in short sections. The overall steady-rate creep for the sliding portion is 0·15 in in 100 000 hours.

The steady-rate creep in 100 000 hours in the half-length of strip is 0·38 in + 0·15 in, i.e. 0·53 in.

The corresponding figure for $\theta_c = 145°$C and a consequent stress of 20 300 lb/in² is 0·70 in. This is an increase of 32% for an increase in temperature from 140°C to 145°C. In long rotors, therefore, in which the maximum stress is determined by the temperature rise, temperature becomes critical at about this level by reason of the marked effect of small increases in stress and temperature in combination above this range.

In rotors too short for locking relative to the slot wedge to occur, the stress is not a function of temperature, which can thus with safety be higher than in long rotors, apart from the fact of the shorter length of strip contributing to creep strain in smaller windings. As indicated in Section 8.2, however, the direction and rate of temperature gradient may be such that the above creep strain rates per inch of strip are exceeded, and this effect is relatively highest in medium-size windings.

(10) PERMISSIBLE LIMITS OF DEFORMATION

It is obviously difficult to arrive at any reasoned safe limit for estimated shortening of turns over the presumptive life of a machine. Apart from the fact that there is no experience of failure through deformation of c.w.s.b. copper windings to serve as a guide, failure may occur, as with windings of ordinary copper, in several ways: namely, contact between neighbouring stacks, collapse of stacks through differential shortening of turns, or cracking at the corners of the end turns. In regard to this last action it may be noted that the ductility of 10–25% c.w.s.b. copper is somewhat higher than that of tough-pitch copper of equal hardness.[7]

Failure has been recorded through shortening of as little as 0·8 in at one end of a winding of ordinary copper, though the failure at this stage did not call for more than localized repairs. Complete replacement of windings appears to have become unavoidable when shortening, as manifested at one end of the winding, reaches a local maximum of the order of 2 in; but, in the author's experience, this stage has been the culmination of several failures, and complete renewal in such cases would have been effected much earlier had this been practicable.

A further difficulty in suggesting a working limit of estimated deformation is that neighbouring turns or batches of turns in the same or adjacent slots are often found to have moved erratically in relation to each other. This action is illustrated in Fig. 5,

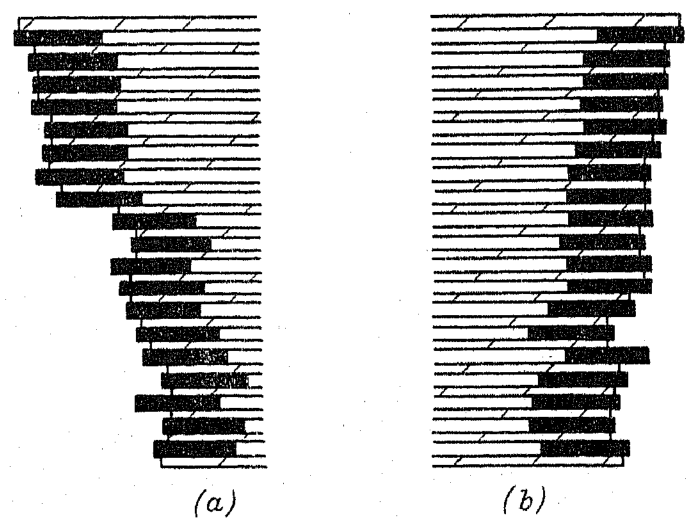

Fig. 5.—Typical distortion effects at opposite ends of coil.

(a) Coupling end.
(b) Exciter end.

which shows how the landing of adjacent turns of a winding was finally reduced in this case to about one-quarter of the width of the strip, with danger of collapse of the stack.

This irregularity of movement may be due, at any rate in part, to displacement of the mid-length points of the strips concerned.

In long rotors, locking at speed of the mid-length portions of the turns before heating starts will tend to prevent such bodily movement during the running period; but in both long and short rotors the winding will be free from this central anchoring effect during the cooling period at standstill, and contraction of the winding may therefore be unsymmetrical irrespective of the length of the rotor. Probably through this action the observed displacement of individual end-turns at one end or the other is often greater than the deformation contributed by the half-length. With directly-cooled windings, which can be effectively cooled at speed before shutting down, the discrepancy should be less than with conduction cooling.

While it seems that no definite limit can be laid down for the safe amount of copper shortening, it is suggested that a nominal figure of 0·5 in over 100 000 hours for the half-length of winding is excessive, bearing in mind that the operating life of many machines is well in excess of this period. Thus either the average temperature rise or the temperature gradient in rotors of this size should be lower than the figure assumed in this case.

The work of Benson, McKeown and Mends[7] and of other investigators, including designers and operating engineers, has established the appropriate silver content and hardness of silver-bearing copper for rotor windings. Further, as the processes of winding deformation have become more fully understood, the safe ranges of operating stress and temperature can be defined, as is attempted in this paper, within narrowing limits. There is evidently a need at this point for further work on creep rates of 10% cold-worked 0·1% silver-bearing copper over a small range of temperature, say up to 150°C, at stresses up to about 25 000 lb/in^2. The estimates of the previous Section indicate that operating conditions anywhere near these levels cannot safely be combined in large rotors; but in small and medium-size rotors the position is different, as already indicated.

Benson, McKeown and Mends's paper[7] and the discussion afford some ground for concluding that the steady creep rates measured over the periods stated in the paper (which in only a few tests amounted to as much as 10 000 hours) hold over the presumptive life period of a machine: further creep investigations might, however, with advantage include a number of especially-long-term tests to confirm this. In any case the tests require to be of sufficient duration to enable the initial creep and steady-rate creep effects to be clearly separated. With the limited ranges suggested it might be practicable to test the specimens in compression and so obviate possible inaccuracies due to assumptions regarding the effects of differences in direction of stress at cold working and testing.

(11) THE PROBLEM OF TEMPERATURE MEASUREMENT IN ROTOR WINDINGS

A basic difficulty which from the beginning has complicated investigations into the problem of copper shortening is the lack of knowledge of the temperature distribution through the winding, due to the fact that resistance readings give the average temperature rise over the whole winding. Many attempts have been made to formulate temperature-distribution curves, but the conditions governing heat flow in conduction-cooled windings under running conditions are complex.

With these difficulties in mind it is suggested that in prototype conduction-cooled rotors the winding be divided into two circuits, the portions which observations of discarded windings have shown to be at the highest temperature being combined in one circuit. This arrangement would involve an additional slip ring and a special arrangement of end-turn connections to link these hot sections, which, in general, are the near-bottom turns of those stacks most remote from the pole faces. It might be worth while to effect trial changes in these connections in order to obtain more complete and decisive data: relatively few machines would be involved in these special measures.

If excessive temperature gradients were found to exist in conduction-cooled windings, the dual circuit might be used to modify the temperature distribution by adjustment of the relative current densities in the two circuits.

Further information of value might be obtained by the insertion of temperature indicators (based possibly on the colour-change principle) in small-bore plugged test holes in the rotor teeth. Whether or not indicators could be devised to afford information on temperature relations at various levels of the stacks, it should be possible to show whether the slot-strip temperatures are in fact constant over the strip length, as appears usually to be assumed. It is clearly important, especially in long rotors, to design the cooling system so as to limit the temperature in the mid-length regions of the winding to, at any rate, no higher level than in the outer portions.

(12) CONCLUSIONS

The criterion of maximum stress in a given slot strip of a large rotor winding operating within the elastic limit of the material is the temperature rise of the strip relative to the rotor iron, and not the rise relative to the top strip as suggested elsewhere. The direction and rate of the temperature gradient have, however, a bearing on the stress distribution along a slot strip for a given turn temperature.

For the avoidance of excessive deformation rates in large rotor windings of c.w.s.b. copper, the temperature rise in the hottest turns should not exceed the limit of average temperature rise of B.S. 225. It is therefore desirable that methods be found for measuring and controlling zone temperatures in conduction-cooled windings.

Two-shift operation is not appreciably more conducive to deformation in c.w.s.b. copper windings than weekly or even longer operating cycles.

(13) ACKNOWLEDGMENTS

For assistance in the recovery and examination of rotor windings at the discard stage, and especially in the development of a special routine of removal of windings from the rotor slots with a minimum effect on the condition of the material, the author is grateful to members of the staff of the Electricity Supply Commission of the Union of South Africa; also to the Bureau of Standards, Pretoria, for carrying out many of the tests of hardness and elastic strength on these windings. To Mr. W. D. Horsley the author's thanks are due for information used and referred to in the paper.

Acknowledgment is also made to the British Non-Ferrous Metals Research Association, the Copper Development Association, and the South African Council for Scientific and Industrial Research for metallurgical and other data; and to the manufacturers of turbo-alternators in Great Britain and the United States for information on design developments and operating experience. Finally, the author thanks the Electricity Supply Commission of the Union of South Africa for permission complete the investigations and to publish the paper.

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(15) APPENDICES

(15.1) Stress Analysis for Rotor Winding operating within the Elastic Limit

(15.1.1) Turn Stress when Copper/Iron Differential Expansion is zero.

In operating temperature range,

E for copper $= 16\cdot0 \times 10^6$lb/in^2.

Coefficient of expansion of copper $= 0\cdot0000170$ per 1°C.

Coefficient of expansion of iron $= 0\cdot0000115$ per 1°C.

Then $e = 0\cdot0000170(\theta_c - \theta_0) - 0\cdot0000115(\theta_i - \theta_0)$ in/in.

$$Ee = 272\theta_c - 184\theta_i - 88\theta_0 \text{lb/in}^2 \quad . \quad . \quad . \quad (7)$$

(15.1.2) Stress Distribution in Successive Turns: Cases (i) and (ii).

The cross-section of the winding strip is assumed in this analysis to be uniform. Variations in cross-section between strips (e.g. in graded windings) can easily be taken into account in numerical computations. Where the cross-section is not uniform along the strip (as in strips slotted at intervals to form radial ventilation ducts when assembled) the average value of centrifugal force along the strip is applicable; but the stresses in the solid portions of the strips and the higher values in the reduced cross-sections must be calculated separately for the purpose of creep-rate estimates, since the relation between creep rate and stress is far from linear at the higher values of stress and temperature which can apply in practice.

It is convenient to remember that in a group of turns where the temperature increases towards the lowest turn, and there is no compensating rise in $\mu\Sigma F$ (which requires a substantial increase in μ_t at successive interfaces), the hotter the turn the nearer to mid-length lies its locking point relative to the slot wedge.

The factors determining the relative limits of locking between strips (as distinct from locking relative to the slot wedge) are noted as they arise in the analysis.

Since the operating stresses are within the elastic strength of the material, the stresses in those portions of the winding, if any, that are completely restrained from expanding relatively to the rotor body are proportional to the differential temperature rise in the particular turn.

It is assumed in the analysis that the tensile strain in the rotor body is small in comparison with the compressive strains in the winding strips. This can readily be shown by applying the results of analysis on this basis to practical operating conditions and deducing the body strain from the aggregate of the maximum turn stresses derived therefrom.

The winding is taken to be in its initial condition, i.e. free from deformation, so that the end packings impose no stress in the slot strips. The comparative effects of forces exerted by the end packings as a result of contraction in windings of ordinary copper and c.w.s.b. copper respectively are discussed in Section 5.2. Side friction on the slot strips appears to be small in all the windings examined, and is neglected in the analysis.

Case (i).

$\mu_{w.1} < \mu_{1.2}$ to the extent that $\mu_{w.1}\sum_m^1 F < \mu_{1.2}\sum_m^2 F$; thereafter $\mu\Sigma F$ decreases at successive interfaces down stack. Temperature rises from top turn to point near bottom of stack and thereafter falls, as in Table 1.

Since the frictional force between the slot wedge and the top turn is less than that between turns Nos. 1 and 2 at the same distance from the coil end, and the temperatures in the upper turns increase with depth of turn, the top strip will be in tension in the portions of its length over which sliding of both faces occurs. In a sufficiently long rotor the central portion of the stop strip is locked to the slot wedge, provided that $\mu_{w.1} > 0$, and is therefore subject to compressive stress Ee_1. The tensile force in the end portions of turn No. 1 must therefore disappear at some point in the turn, and this change can occur only because $l_2 < l_1$, for, so long as sliding continues on both faces of turn No. 1, the tensile stress in this turn continues to increase towards mid-length owing to the increasing excess of the outward friction force on its lower face over the inward friction force on its upper face.

Thus, in the present case, No. 2 turn locks with No. 1 turn while No. 1 turn still slides on the slot wedge. The number of strips subject to inter-turn locking at points outwards of point l_1 is determined by the limiting condition that the stress in any strip cannot exceed the value Ee. The sequence of these locking points is shown in Fig. 6.

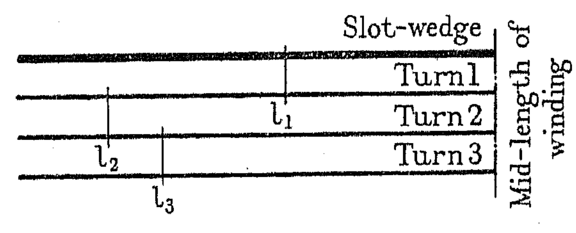

Fig. 6.—Locking points of slot stack interfaces—case (i), top group.

The first step in the analysis is to derive expressions for l_2, p_{l12}, p_{2l2} and $l_3, p_{l13}, p_{2l3}, p_{3l3}$. By inspection of these equations the general expressions for l and p_l can be written for any turn in this top group, i.e. to the stage where the stress reaches Ee.

ap_{l12} = resultant of frictional forces on upper and lower faces of turn No. 1 at point l_2.

(Inward direction of force positive, outward direction negative.)

$$\text{Therefore} \quad ap_{l12} = l_2\left(\mu_{w.1}\sum_m^1 F - \mu_{1.2}\sum_m^2 F\right) \quad . \quad . \quad . \quad (8)$$

If turn No. 1 could expand freely its expansion would be e_1. Therefore expansion of turn No. 1 under stress p_{1l2} is $e_1 - (p_{1l2}/E)$. From point l_2 inwards turn No. 2 is locked to turn No. 1, and turns Nos. 1 and 2 therefore expand equally within that point.

Thus the strain in turn No. 2 at point l_2 is $e_2 - \left(e_1 - \frac{p_{1l2}}{E}\right)$

and
$$p_{2l2} = Ee_2 - Ee_1 + p_{1l2} \quad . \quad . \quad . \quad . \quad (9)$$

Also, ap_{2l2} is the resultant of sliding-friction forces on upper and lower faces of turn No. 2 at point l_2, since sliding occurs up to l_2 on its upper face, and, with a rising temperature gradient down the stack, to a point inwards of l_2 on its lower face.

Thus
$$ap_{2l2} = l_2\left(\mu_{1.2}\sum_m^2 F - \mu_{2.3}\sum_m^3 F\right) \quad . \quad . \quad . \quad (10)$$

From eqns. (8), (9) and (10), by equating and substituting for p_{1l2},

$$l_2\left(\mu_{1.2}\sum_m^2 F - \mu_{2.3}\sum_m^3 F\right) = a(Ee_2 - Ee_1) + l_2\left(\mu_{w.1}\sum_m^1 F - \mu_{1.2}\sum_m^2 F\right)$$

$$l_2 = \frac{a(Ee_2 - Ee_1)}{2\mu_{1.2}\sum_m^2 F - \mu_{2.3}\sum_m^3 F - \mu_{w.1}\sum_m^1 F} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

l_2 being evaluated, p_{2l2} is given by eqn. (10), and p_{1l2} by eqn. (9).

From point l_2 inwards turns Nos. 1 and 2 are locked together and can be treated, in relation to forces external to them, as a single turn of cross-section $2a$. The expansion of combination 1,2 at point l_3 is

$$\frac{e_1 + e_2}{2} - \frac{p_{1l2} + p_{2l2}}{2E}$$

and this is also the expansion of turn No. 3 at this point.

Therefore
$$p_{3l3} = Ee_3 - \frac{Ee_1 + Ee_2}{2} + \frac{p_{1l2} + p_{2l2}}{2} \quad . \quad . \quad (9a)$$

The procedure already followed for turns Nos. 1 and 2 at point l_2, applied to turns Nos. 1 to 3 at point l_3, then gives the following relations

$$p_{3l3} = \frac{l_3\left(\mu_{2.3}\sum_m^3 F - \mu_{3.4}\sum_m^4 F\right)}{a} \quad . \quad . \quad (10a)$$

and
$$l_3 = \frac{a(2Ee_3 - Ee_1 - Ee_2)}{3\mu_{2.3}\sum_m^3 F - 2\mu_{3.4}\sum_m^4 F - \mu_{w.1}\sum_m^1 F} \quad . \quad (11a)$$

From inspection of eqns. (10), (11), (10a) and (11a) the general expressions for the sliding lengths and the turn stresses in this top group can be be written as follows:

$$l_n = \frac{a\left[(n-1)Ee_n - \sum_1^{n-1} Ee\right]}{n\mu_{n-1.n}\sum_m^n F - (n-1)\mu_{n.n+1}\sum_m^{n+1} F - \mu_{w.1}\sum_m^1 F} \quad (12)$$

and
$$p_{nln} = \frac{l_n\left(\mu_{n-1.n}\sum_m^n F - \mu_{n.n+1}\sum_m^{n+1} F\right)}{a} \quad . \quad . \quad (13)$$

The stresses at points l_n in the turns above turn n bear the same relations to p_{nln} as the values of Ee for the respective turns.

At some stage (turn x, say) in the numerical calculations for the above group the turn stresses corresponding to the value of lx derived from eqn. (12) will, in long rotors, exceed Ee for the respective turns. This value of l is thus shown to exceed l_1, and is therefore too high, owing to the assumption of sliding of turn No. 1 on the slot wedge having been carried too far. Turn No. x is therefore the bottom turn of this group, and the true value of l_x is l_1. At points l_1 in turns Nos. 1 to x the stresses attain the values Ee for the respective turns, and since sliding occurs on the upper face of turn No. 1 up to point l_1 and on the lower face of turn x up to a point inwards of l_1 (turn $x + 1$ being hotter than turn x),

$$l_1 = \frac{a\sum_x^1 Ee}{\mu_{w.1}\sum_m^1 F - \mu_{x.x+1}\sum_m^{x+1} F} \quad . \quad . \quad . \quad (14)$$

The next step is the evaluations of l in turns ($x + 1$) to the turn next above the hottest turn [but see note at end of analysis of case (i); also Section 15.2].

In this group $l > l_1$, thus inwards of points l the differential expansions are zero and the stresses are Ee. Also, since the temperature increases in successive turns of this group, l also increases turn by turn. The equations of sliding thus apply at points l for both faces of these turns. In turn ($x + 1$), for example,

$$l_{x+1} = \frac{aEe_{x+1}}{\mu_{x.x+1}\sum_m^{x+1} F - \mu_{x+1.x+2}\sum_m^{x+2} F} \text{ and so on } . \quad (15)$$

There now remains the bottom group of turns in which the temperature decreases to the bottom turn.

To avoid unnecessary complication in the use of symbols for this group, numbers 10 to 13 are used to identify the bottom turns, in which the temperature is assumed to fall from 10 onwards. Nothing is lost thereby as regards generality of application of the method.

The procedure for turns Nos. 10–13 is as follows:

In Fig. 7, points 10, 11, 12 and 13 show the sequence of the

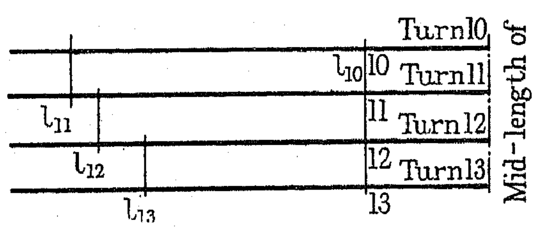

Fig. 7.—Locking points of slot stack interfaces—case (ii), bottom group.

limits of locking of turns Nos. 10–13 relative to the slot wedge, and l_{10}, l_{11}, l_{12} and l_{13} the locking points between turns. Point 10 in this case is the same as point l_{10}.

If the upper face of turn No. 10 outwards of point l_{10} slides on turn No. 9 [see note at end of analysis of case (i)], the sum of the forces in turns Nos. 10 to 13 at point l_{10} is equal to the friction force on the upper face of turn No. 10 at point l_{10}; thus

$$l_{10}\mu_{9.10}\sum_{13}^{10} F = a(Ee_{10} + Ee_{11} + Ee_{12} + Ee_{13}) \quad . \quad (16)$$

from which l_{10} can be evaluated.

The central portions of turns Nos. 10–13 locked relatively to the slot wedge have the same length since turn 10 undergoes differential expansion from point 10 outwards, and the lower

turns, being based upon turn 10, must also expand from point 10 outwards.

The sequence of the limits of locking between turns and relative to the slot wedge is determined as follows.

Since turns Nos. 13 and 12 are at different temperatures, and the frictional restraining force is zero at the ends, sliding occurs between these turns at their extreme ends; and because turn No. 13 is cooler than turn No. 12 the expansion of the end portion of turn No. 13 is less than that of turn No. 12. The sliding end-portion of turn No. 13 therefore moves inwards relatively to turn No. 12 and is thus in tension. Now the stress difference between two turns locked together is the same at all corresponding points throughout the locked length. The stress is zero at the ends of the turns, and since the rate of accretion of frictional restraint on turn No. 13 is no greater than on turn No. 12 (it is in fact slightly less), it must continue at the maximum rate (i.e. through sliding) on turn No. 13 after turn No. 12 has ceased to slide on turn No. 11. Thus l_{13} must be nearer the mid-length point than l_{12}. Similarly, l_{12} is nearer mid-length than l_{11}, and l_{11} than l_{10}.

Between points 13 and l_{13} the expansions of turns Nos. 10 to 13 are equal.

Expansion of turn No. 10 at point l_{13} is $e_{10} - \dfrac{p_{10/13}}{E}$.

Therefore
$$p_{11/13} = Ee_{11} - Ee_{10} + p_{10/13} \quad . \quad . \quad . \quad (17)$$
$$p_{12/13} = Ee_{12} - Ee_{10} + p_{10/13} \quad . \quad . \quad . \quad (18)$$
$$p_{13/13} = Ee_{13} - Ee_{10} + p_{10/13} \quad . \quad . \quad . \quad (19)$$

Since turn No. 10 slides on turn No. 9 at point l_{13},
$$a(p_{10/13} + p_{11/13} + p_{12/13} + p_{13/13}) = \mu_{9.10} l_{13} \sum_{13}^{10} F \quad . \quad (20)$$

Substituting from eqns. (17), (18) and (19),
$$a(4p_{10/13} + Ee_{11} + Ee_{12} + Ee_{13} - 3Ee_{10}) = \mu_{9.10} l_{13} \sum_{13}^{10} F \quad (21)$$

Also, since turn No. 13 slides on turn No. 12 at point l_{13},
$$ap_{13/13} = -\mu_{12.13} l_{13} F_{13} \quad . \quad . \quad . \quad . \quad (22)$$

(Negative sign because sliding is inward.)

From eqns. (19), (21) and (22) l_{13} and $p_{10/13}$, $p_{11/13}$, $p_{12/13}$ and $p_{13/13}$ can be evaluated.

Similarly, l_{12} and l_{11} and the corresponding stresses in turns Nos. 10–12 can be derived.

Note.—As already noted, with a temperature gradient falling from turn No. 10 to turn No. 13, these turns operate within point l_{13} as a composite turn at their average temperature. If this average is lower than the temperature of turn No. 9, l_9 will be less than l_{10} and turn No. 9 should then be included in the composite bottom group 9–13. In the case selected for complete analysis and computation this condition applies, but the temperature difference in question is small and the adjustment has been omitted. Section 15.2 deals with an example in which the condition applies to several turns above the hottest turn, and is taken into account in the computation.

Case (ii).

As Case (i), except that the temperature is uniform throughout the stack.

All turns, being at the same temperature, expand equally, and sliding occurs only between the top turn and the slot wedge. The stress distribution is therefore the same in all strips.

Frictional resistance to sliding exerted by the slot wedge on the top turn at a point distant l in from end is $\mu_{w.1} l \sum_{m}^{1} F$.

Sum of forces in m strips at points distant l in from end is map_l with the proviso that p_l cannot exceed Ee for any value of l.

Then
$$map_l = \mu_{w.1} l \sum_{m}^{1} F \quad . \quad . \quad . \quad . \quad . \quad (23)$$
$$p_l = \frac{\mu_{w.1} l \sum_{m}^{1} F}{ma} \quad . \quad . \quad . \quad . \quad . \quad (24)$$

If the rotor is large enough $p_l = Ee$

Then
$$l = \frac{maEe}{\mu_{w.1} \sum_{m}^{1} F} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

The half-length of the locked portions of the strips is $(l_s - l)$.

The stress in each strip falls uniformly from point l to zero at the end.

(15.2) Stress Distribution in Hottest Turn when Temperature decreases towards Bottom of Stack

The winding dimensions and the starting conditions are again as set out in Table 1. The temperature distribution and the corresponding values of Ee are given in Table 2. $\mu = 0{\cdot}25$ at all interfaces.

It is shown in the general analysis, Section 15.1.2, that sliding between turns in which the temperature falls in the direction of the lowest turn is limited to short end-portions.

With the temperature distribution of the present case group 13 to 3 inclusive comprises the minimum number of turns, starting from the bottom of the stack, in which the average temperature exceeds the temperature of the next turn above. Group 13 to 3 can therefore be treated, except for the short end-portions, as a single turn, its average temperature being 117°C and the corresponding value of Ee approximately 13 000 lb/in^2.

Since group 13 to 3 is at a higher average temperature than turn No. 2, l_3, the sliding length of group 13 to 3 on turn No. 2 is given by
$$1\,087 l_3 = 0{\cdot}3 \times 13\,000 \times 11 \quad . \quad . \quad . \quad (26)$$
$$l_3 = 39 \text{ inches}$$

At point l_{13}, the starting-point of sliding of turn No. 13 on turn No. 12, friction on face of turn No. 13 is equal to the force in turn No. 13.

Thus
$$89 l_{13} = -0{\cdot}3 p_{13/13}$$
$$300 l_{13} = -p_{13/13} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

(Negative sign is required because turn No. 13 slides inwards on turn No. 12.)

If the stress in turn No. 3 at point l_{13} were zero, the expansion of turn No. 3 at that point would be e_3.

Under stress $p_{3/13}$ the expansion of turn No. 13 at point l_{13} is
$$e_3 - \frac{p_{3/13}}{E} \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

Since turns Nos. 13 to 3 expand equally at point l_{13},
$$p_{4/13} = Ee_4 - (Ee_3 - p_{3/13}) \quad . \quad . \quad . \quad . \quad (29)$$
$$= 15\,000 - 13\,000 + p_{3/13}$$
$$p_{4/13} = 2\,000 + p_{3/13}$$
$$p_{5/13} = 4\,000 + p_{3/13}$$
$$p_{6/13} = 6\,000 + p_{3/13} \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

$$
\begin{aligned}
p_{7l13} &= 4\,000 + p_{3l13}\\
p_{8l13} &= 2\,000 + p_{3l13}\\
p_{9l13} &= 0 + p_{3l13}\\
p_{10l13} &= -2\,000 + p_{3l13}\\
p_{11l13} &= -4\,000 + p_{3l13}\\
p_{12l13} &= -6\,000 + p_{3l13}\\
p_{13l13} &= -8\,000 + p_{3l13} \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)
\end{aligned}
$$

Therefore $a\sum_{13}^{3} p_{l13} = 0\cdot3(11p_{3l13} - 2\,000)$ . . . (32)

Equating frictional force between turns Nos. 3 and 2 at point l_{13} to sum of forces in turns Nos. 13 to 3 at point l_{13},

$$
\begin{aligned}
1\,087l_{13} &= 0\cdot3(11p_{3l13} - 2\,000)\\
p_{3l13} &= 330l_{13} + 200 \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)
\end{aligned}
$$

From eqns. (31) and (33),

$$
\begin{aligned}
p_{13l13} + 8\,000 = p_{3l13} &= 330l_{13} + 200\\
p_{13l13} &= 330l_{13} - 7\,800 \quad . \quad . \quad . \quad . \quad (34)
\end{aligned}
$$

From eqns. (27) and (34),

$$
\begin{aligned}
300l_{13} &= -p_{13l13} = 7\,800 - 330l_{13}\\
l_{13} &= 12\,\mathrm{in}
\end{aligned}
$$

From eqn. (33), $p_{3l13} = 4\,000\,\mathrm{lb/in^2}$

From eqn. (30), $p_{6l13} = 10\,000\,\mathrm{lb/in^2}$

It is unnecessary to evaluate l_{12}, l_{11}, etc., since these lengths cannot exceed l_{13} and the stress distribution in these short end-lengths is of no significance.

If turns Nos. 6 to 13 were all at the maximum temperature, 140°C, the sliding length of turn No. 6 would be given by

$$
l_6 = \frac{0\cdot3 \times 19\,000}{871 - 766} = 54\,\text{inches}
$$

In the latter case the stress in turn No. 6 would fall uniformly from point l_6 to the end of the turn.

The stress curve for turn No. 6 for each distribution of temperature is shown in Fig. 3.

DISCUSSION ON

"THE PROPAGATION OF SURGE VOLTAGES THROUGH HIGH-SPEED TURBO-ALTERNATORS WITH SINGLE-CONDUCTOR WINDINGS"*

Dr. T. J. Lewis (*communicated*): The theory given by the author to support his experimental results suffers from several errors which make any agreement with experiment fortuitous.

The full development of a winding (Fig. 1) shows that a surge voltage entering a given phase winding will, after partial transfer to the other coil in the same entry slot, cause a disturbance to propagate in both positive and negative directions. Thus Fig. 2 requires modification at a phase terminal in accordance with Fig. A. Both the point of entry and the neutral impedance Z produce a discontinuity in the uniform network, and the boundary conditions at such points will be vital factors in determining the response of the winding. If such conditions are included, a network of the homogeneous two-dimensional type results, for which the formal solution has been indicated by van der Pol and Bremmer.† A more detailed solution for the present case is too complex for practical application, but this does not justify the neglect of all such conditions by the author.

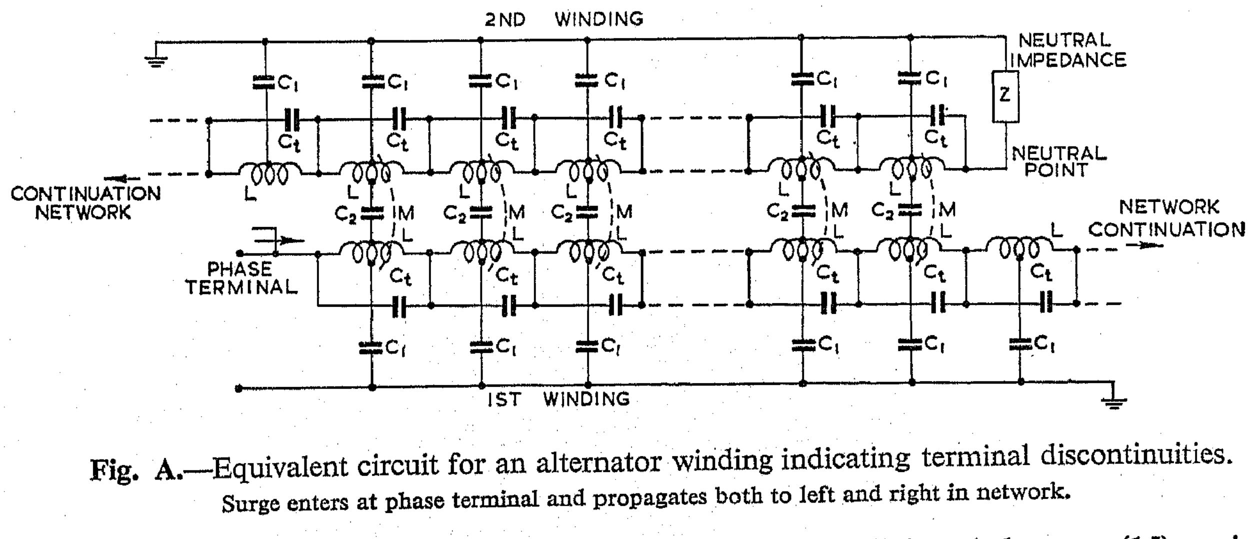

Fig. A.—Equivalent circuit for an alternator winding indicating terminal discontinuities.
Surge enters at phase terminal and propagates both to left and right in network.

There are, however, more fundamental errors. While it is shown that a possible solution of the voltage equations can be expressed as the sum of four terms of the form $E\varepsilon^{j\omega(t\pm x/v)}$ [eqns. (10) and (11)] the correct response to a unit function voltage is, in the first winding, say $e_1(m, t)$, where

$$
e_1(m, t) = \frac{1}{\pi}\int_0^{\infty} E_1(m, \omega)\frac{\sin \omega t}{\omega}d\omega,\ 0 \leqslant m \leqslant N
$$

in which m designates the position in the winding. Now $E_1(m, \omega)$ is a function of m and ω, and also of the boundary conditions, and it cannot be removed from under the integral sign. Thus eqns. (16) and (17) and also eqn. (15) are incorrect. Furthermore, as a result of the integration, although $e_1(m, t)$ may contain only discrete frequency components with an upper limit ω_a, it is not permissible to change the integration limit to ω_a since higher-frequency components make a vital contribution.†

* Robinson, B. C.: Paper No. 1561 S, October, 1953 (see 100, Part II, p. 453).
† van der Pol, B., and Bremmer, H.: "Operational Calculus based on the Two-Sided Laplace Integral" (Cambridge University Press, 1950).

† Lewis, T. J.: "The Transient Behaviour of Ladder Networks of the Type representing Transformer and Machine Windings," *Proceedings I.E.E.*, Paper No. 1691 S, October, 1954 (101, Part II, p. 541).

Again, the true nature of the waves given by eqn. (5) appears to have been overlooked. These are sinusoidal waves which exist spatially throughout the network even at $t = 0$, and it is incorrect to suppose that the voltage "entering" the winding can be deduced from the magnitudes given by eqns. (10) and (11).

The fact that recorded voltages indicate an approximate travelling wave must be related to $e_1(m, t)$ above, and not to eqn. (5) or any arbitrary combination as in eqns. (16) and (17). In the same way eqn. (26) is not applicable. The author has in any case omitted the necessary condition for an approximate travelling wave, namely $C_t \ll C_1$.

Lastly, the experiments described in Section 6.2 are open to criticism. The object of interposing a line is to separate the effects of the impulse generator from the alternator and to ensure that the test impulse is applied from a low-impedance source. To achieve this the length of the line must be such that, after the initial surge along it, subsequent reflections should arrive back at the alternator at times greater than those under consideration, i.e. after approximately 0·5 microsec, corresponding to the wavefronts of the records shown in Fig. 13. Since the time of travel of a surge on the 8 yd line employed would be approximately $2 \cdot 5 \times 10^{-8}$ sec, about 10 reflections reach the alternator during the wavefront. The impulse generator and alternator are thus closely connected, and recorded voltages must be attributed to the combined impedances of impulse generator, alternator and line together. To achieve the original object a line at least 82 yd long is required.

Dr. B. C. Robinson (*in reply*): I am sorry that Dr. Lewis cannot agree with the theory given in the above paper for the propagation of surge voltages through an alternator winding. I suggest that this is due to a failure to appreciate the limitations imposed by the sine-integral solution used and possibly to difficulties caused by a confusion of symbols which occurs in the text.

The form of sine integral* used in the paper to define a step waveform rising from zero to unity at time $t = 0$ is given by

$$\frac{2}{\pi}\int_0^\infty \frac{\sin \omega t}{\omega} d\omega \quad . \quad . \quad . \quad . \quad . \quad . \quad (A)$$

The harmonic components are taken as non-existent for negative values of the variable t since the time $t = 0$ is defined as the instant of application of the surge to the winding. (This is a definite contradiction to Dr. Lewis's comment in his fourth paragraph.) If the higher component frequencies are removed from this expression that plotted in Fig. 4 is obtained. Thus the portion of a hypothetical rectangular wave of amplitude E which would enter the winding as a typical travelling wave is given by eqn. (13), where ω_a is the cut-off, or critical, frequency. It must be realized that this expression is valid only at the terminal and that the shape of the travelling wave changes as it goes through the winding owing to the various velocities of its harmonic components. Now eqn. (10) shows that two sets of sinusoidal components with amplitudes E_a and E_b of frequency ω (where ω is less than the critical frequency) can travel forward into the winding simultaneously with velocities v_a and v_b, i.e. the component sinusoidal voltage travelling forward will be given by

$$e_1 = E_a\varepsilon^{j\omega\left(t-\frac{x}{v_a}\right)} + E_b\varepsilon^{j\omega\left(t-\frac{x}{v_b}\right)} \quad . \quad . \quad . \quad (B)$$

$$e_2 = E_a\varepsilon^{j\omega\left(t-\frac{x}{v_a}\right)} - E_b\varepsilon^{j\omega\left(t-\frac{x}{v_b}\right)} \quad . \quad . \quad . \quad (C)$$

The total voltage entering the winding will of course be the sum of all these components within the range between zero and the critical frequency. This may be obtained by combining these equations with eqn. (13). In the paper this is given by eqns. (16) and (17) for a hypothetical rectangular applied voltage:

$$e_1 = \frac{2E_a}{\pi}\int_0^{\omega_a} \frac{\sin \omega\left(t - \frac{x}{v_a}\right)}{\omega} d\omega + \frac{2E_b}{\pi}\int_0^{\omega_b} \frac{\sin \omega\left(t - \frac{x}{v_b}\right)}{\omega} d\omega \quad . \quad . \quad . \quad . \quad (16)$$

$$e_2 = \frac{2E_a}{\pi}\int_0^{\omega_a} \frac{\sin \omega\left(t - \frac{x}{v_a}\right)}{\omega} d\omega - \frac{2E_b}{\pi}\int_0^{\omega_b} \frac{\sin \omega\left(t - \frac{x}{v_b}\right)}{\omega} d\omega \quad . \quad . \quad . \quad . \quad (17)$$

It will be noted that in making this substitution the meaning of the symbols E_a and E_b has been unintentionally changed. In eqns. (10), (11), (B) and (C) they represent the crest value of the sinusoidal component of frequency ω, but in eqns. (16) and (17) they are used to represent the mean value of the sine integrals as would be indicated by an ordinate of unit height in Fig. 4. [The rectangular applied voltage would be $(E_a + E_b)$.] The first meaning, i.e. the sinusoidal component amplitude, is applicable in all other equations in the paper and its sequel.* These initial penetrating waves are reflected and refracted according to the normal rules at the discontinuities in the winding such as the star point and the line terminals. The latter phenomenon has not been dealt with in the paper itself since it was considered that the complexities produced by the mutual couplings in the winding would render any precise quantitative attempt at evaluation of voltages valueless.

I am afraid I cannot agree with Dr. Lewis's expression for e_1 since the meaning of the symbol $E_{1(m\omega)}$ is not defined, but I think the point is covered in the above explanation. It should perhaps be stated that the term $2E/\pi\omega$ in the sine integral terms applies only to a rectangular wave, and must be replaced by an expression obtained by a Fourier expansion of the applied wave if another applied voltage waveform is considered.

I quite agree with the remarks about the surge voltage in the first winding inducing disturbances travelling in both directions in the second winding. This is already mentioned in Section 3.2. It is obviously in order for Fig. 2 to be modified as in Fig. A, but at the same time it is superfluous. It has already been pointed out by Rudenberg† that it is not necessary to consider the end-connections when deriving the equations for the propagation of the sub-critical component voltages using the travelling-wave theory. Both diagrams must be considered as approximations since each winding is really linked alternately with two other windings as is shown in Fig. 1.

As to the omission of any theoretical treatment of the distribution of the supercritical frequencies in the winding, this was done on the evidence provided by the tests. These were carried out with a large-capacitance impulse generator and the shortest possible lead between the impulse generator and the machine terminals. Even under these conditions, which were considered to represent the lowest possible input feed impedance, definite deformation of the wavefront occurred, which appeared to correspond to the cut-off effect of the machine winding. It was therefore decided that any theoretical analysis of the distribution of the supercritical components would be merely academic.

Finally, regarding the criticisms of the use of the 8 yd line, this was included to increase the impedance of the source of the

* CHURCHILL, R. V.: "Fourier Series and Boundary Value Problems" (McGraw-Hill Book Co., New York, 1941). P. 91.

* ROBINSON, B. C.: "The Propagation of Surge Voltages through Large Turbo-Alternators with Two Parallel Windings," *Proceedings I.E.E.*, Paper No. 1667 S, June, 1954 (101, Part 2, p. 335).

† RUDENBERG, R.: Discussion to Reference 4, *Transactions of the American I.E.E.*, 1940, 59, p. 1260.

surge at the alternator terminals, and not to decrease it as suggested by Dr. Lewis. Reflections would, of course, occur at the alternator terminals and again at the impulse generator with the reflected wave reaching the machine terminals about 5×10^{-8} sec after its original reflection as suggested by Dr. Lewis. The surge applied to the alternator terminals would then consist of the incoming surge plus the sum of previous reflected voltages. So far as the alternator was concerned, these incoming voltages could be replaced by an incoming surge of the same equivalent waveform which had come from a relatively-high-impedance source giving the same waveform. In both cases the wave which would enter the winding would still contain only components of frequency less than the critical frequency. Thus it may be anticipated that the extrapolation as explained in Section 6.2 would give a value for the wavefront penetrating the alternator winding when a rectangular wave was applied to the connected line.

DISCUSSION ON "THE TRANSIENT BEHAVIOUR OF LADDER NETWORKS OF THE TYPE REPRESENTING TRANSFORMER AND MACHINE WINDINGS"*

Dr. B. C. Robinson (*communicated*): The paper gives another derivation of the familiar standing-wave theory for the penetration of surge voltages into electrical machines. The form of circuit which the author gives lends itself to convenient construction of model circuits. He extends the theory to cover the case of a network consisting of a small number of units. This would appear to have a possible application to shell-type transformers. Most large transmission-system transformers built in this country are, of course, of the core type, with either disc- or layer-type windings. The former have a large number of discs and may therefore be conveniently treated as being infinitely divided, and the latter are not dealt with in the paper.

From his equations and statements it appears that the author has failed to grasp the essential difference of conception between the standing-wave theory or its corresponding travelling-wave notation as given in the paper and the travelling-wave theory as devised by Rudenberg† and used by myself.‡ For instance, he comments on the fact that neither Rudenberg nor Robinson takes into account the termination of the network. This has already been explained by Rudenberg§ as being unnecessary in the case of the travelling-wave theory until such times as voltages occur at the terminal concerned and reflection and refraction of the wave occurs. This point is also explained by me|| in a discussion on my paper. In the latter case no mention of the reflections was made in the theoretical portion of the paper, since it was considered that the complications introduced by the machine connections themselves would render any quantitative theoretical treatment inaccurate and therefore useless before such times as reflections occurred. If in any particular winding this was not the case, the theoretical treatment of the reflection does not present any difficulties which are not easily overcome.

Dr. T. J. Lewis (*in reply*): I fail to understand the necessity for Dr. Robinson's comments since most of the matters raised by him can be settled immediately by perusal of the sub-headings of my paper. For instance, Section 3 indicates that the paper is primarily concerned with a network having an arbitrary number of units N, there being no special extension to small values of N. On the contrary, Section 7.2 shows the logical extension of the theory to the case of infinite sub-division ($N \to \infty$). Dr. Robinson has obviously overlooked this.

Again no undue emphasis has been placed on the standing-wave solution, and Sections 4.1 and 4.2 give both the standing- and travelling-wave solutions in a way which indicates their essential equivalence. The conception of the travelling-wave theory given by Rudenberg is identical with that above and any differences which arise are due to faulty procedure by that author. The difficulties experienced by Dr. Robinson in comparing Rudenberg's treatment with the present one appear to be due to a failure to understand the full implications of the mathematical processes involved.

In his contribution Dr. Robinson suggests that the terminal conditions need not be included since the times under consideration are less than those required to produce terminal effects. His original paper imposes no restrictions on the time in this way, and in fact his experimental results indicate clearly that terminal conditions are influencing the result. Failure to produce a precise and rigorous mathematical statement of the problem in the paper by Dr. Robinson leads to fallacious results. A correct use of the superposition principle implied in the Fourier integral will yield solutions valid throughout the network at all times. The correctness of such a solution in no way depends on the choice of a standing- or travelling-wave concept for its expression.

* LEWIS, T. J.: Paper No. 1691 S, October, 1954 (see **101**, Part II, p. 541).
† RUDENBERG, R.: "Performance of Travelling Waves in Coils and Windings," *Transactions of the American I.E.E.*, 1940, 59, p. 1031.
‡ "The Propagation of Surge Voltages through High-Speed Turbo-Alternators with Single-Conductor Windings," *Proceedings I.E.E.*, Paper No. 1561 S, October, 1953 (100, Part II, p. 453).
§ Discussion on paper cited above.† *Transactions of the American I.E.E.*, 1940, **59**, p. 1260.
|| See page 361.

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Paper No. 1745 U
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DESIGN, PERFORMANCE AND APPLICATION OF MINIATURE CIRCUIT-BREAKERS

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SUMMARY

The paper is intended as a critical survey of the technical and economic aspects of miniature circuit-breakers.

After some introductory remarks on their place in the field of protective gear, a brief historic outline of their development is given, followed by an analysis of the many requirements to be met, together with a study of the more important design features to be observed concerning contacts, arc-extinguishing devices, mechanism, etc. Special attention is devoted to overloads and short-circuit-protection devices, and the rupturing capacity is reviewed in some detail.

The application and economy of these circuit-breakers are discussed on a basis of comparison with other protective gear, and with the practice followed in the United States.

In conclusion, some suggestions are made for the future development of miniature circuit-breakers in the belief that they will occupy a place of constantly increasing importance.

(1) INTRODUCTION TO THE MINIATURE CIRCUIT-BREAKER

Overload and short-circuit protection of electric circuits and equipment has in the past been effected principally by electric fuses and circuit-breakers.

The semi-enclosed fuse has the double advantage of being cheap and easily rewireable, but through this latter feature it is also open to abuse due to overwiring well beyond the intended rating. The high-rupturing-capacity fuse largely overcomes this disadvantage and is, moreover, capable of dealing with large fault currents, but is far more costly both initially and in maintenance. In all cases, the repair of a blown fuse is a nuisance and may cause loss of valuable time.

The circuit-breaker, on the other hand, is free from these defects, but has its drawbacks in being far dearer and more cumbersome than a fuse.

The need for some protective device embodying the main advantages of fuses and circuit-breakers is therefore apparent, its aim being to combine the small size and cheapness of a fuse with the dependability and reswitching features of the circuit-breaker. Thus came about the development of miniature circuit-breakers.

(2) HISTORY OF DEVELOPMENT

The first miniature circuit-breaker may be said to date back to the period 1910–25, when small h.v. circuit-breakers were developed, particularly in the United States. They were based on the design of oil circuit-breakers, and were tripped by a fuse element; for that reason they were referred to as liquid fuses, although in truth they were to be regarded as miniature oil-break circuit-breakers.

However, it was not until about 1930* that the design of air-break miniature circuit-breakers such as we know them to-day began almost simultaneously in Britain and in the United States; but while their use spread only slowly in Britain, their progress has been little short of phenomenal in the United States, where they have taken the place of a substantial proportion of fuses and have, in fact, given rise to a m.c.b. consciousness and outlook which has had considerable influence on the design of supply circuits, the general tendency being to keep the prospective short-circuit apparent power of sub-circuits to fairly low values. In fact, it has become general practice to use circuits relying for protection solely on these circuit-breakers, which are referred to as "moulded case" or "frame," rather than miniature, circuit-breakers, since their range stretches from single-pole designs of low current ratings at 110 volts to triple-pole models breaking 600 amp at 600 volts, so that only their physical size would justify the term miniature.

The influence of this development soon made itself felt elsewhere, and the use of miniature circuit-breakers has become standard practice in many countries, some of which have included them in their specifications, e.g. France[1] and Australia;[2] Germany in particular has been well in the fore in this field.

In Britain, the traditional outlook remained severely biased towards fuses, despite serious efforts made to popularize the use of miniature circuit-breakers. Whereas in the United States they were designed with the specific object of replacing fuses, and were thus rectangular in shape and capable of being built into distribution boxes, British manufacturers seemed to be of two minds whether to give them the appearance of a fuse or that of a tumbler switch.

About 1935, some attempts were made to build these early products into distribution boxes or panels, but on the whole they were not really successful, since, in general, the design had not been specifically directed towards this end, although there are one or two noteworthy exceptions.

It would be hardly fair to ascribe this reluctance towards adoption of miniature circuit-breakers entirely to a conservative fuse-minded outlook. Their design presents difficult problems, some of which do not apply to the same extent in the United States, e.g. a higher voltage and higher short-circuit current, and a preference for suitability on both d.c. and a.c. supplies. Furthermore, the 1939–45 War stifled many projects.

The post-war years, however, have seen a sudden spurt in the development of miniature circuit-breakers coupled with the design of distribution boxes, partly under the influence from abroad and partly owing to numerous building schemes and other capital projects.

(3) ESSENTIAL FEATURES

(3.1) General

A miniature circuit-breaker has to meet many requirements, some of which are hard to reconcile. Since it will be generally installed where in the past a fuse or switch-fuse would have been used, it must of necessity be inexpensive—at least relatively so—and small, preferably no larger than a fuse corresponding to its maximum rating. It must be suitable for mass-production and thus capable of easy assembly by semi-skilled labour. The main source of complication lies in the fact that the miniature circuit-breaker has two principal and distinct

* Since the paper was written, further investigation has revealed a much earlier German design, dated 1908–10.

This is an "integrating" paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Wolff is with the M.C.B. Co. (Manchester), Ltd., and was formerly with Dorman and Smith, Ltd. Mr. Atherton is with Dorman and Smith, Ltd.

functions, namely that of a switch and that of a circuit-breaker. As a switch it must be capable of making and breaking its rated current faultlessly a great many times. As a circuit-breaker it must give a thoroughly reliable protection against dangerous overloads and short-circuits.

There is in Britain no standard specification for miniature circuit-breakers as such; there is, however, a British Standard[3] for air-break circuit-breakers generally, and this includes current ratings of 15, 30 and 60 amp, and thus covers the miniature circuit-breaker range.

(3.2) Mechanical Requirements

(3.2.1) Operational.

Miniature circuit-breakers will be used in lieu of fuses, e.g. in distribution boards, in which case it may be taken that they are normally in the "on" position and will be operated only occasionally. The main considerations are then electrical, i.e. efficient protection and current-carrying ability for indefinite periods. The one essential mechanical condition is non-deterioration.

On the other hand, many will be used in lieu of a switch or switch-fuse, and may be called upon to make and break their circuit numerous times, in the same way as a tumbler switch. The mechanical life performance of an ordinary circuit-breaker is deemed satisfactory if all parts are still in working order after 500 operations (B.S. 862, Section 36).[3] Such a low figure would, of course, be entirely unsuitable for a miniature circuit-breaker. On the other hand, where tumbler switches are concerned, a minimum life of 15 000 operations at 5 amp is required,[4] although manufacturers usually endeavour to obtain at least 100 000 operations and some switches are known to have shown a performance of one million operations or more. Such a figure is at present out of the question for a miniature circuit-breaker, in view of the relatively large number of moving parts and springs, compared with a tumbler switch; but the British Standard figure for tumbler switches gives a fair value, which with sound design may be achieved and even considerably exceeded.

(3.2.2) Mechanism.

The mechanism must be of the "trip free" type, so that the contacts cannot be held closed against a fault. It should, moreover, withstand impact and vibration of at least moderate severity, in order to ensure continuity of operation under the diverse conditions likely to be met with in service.

(3.2.3) Physical Size.

Overall dimensions vary appreciably from one make to another and depend, amongst other factors, to a considerable extent upon the voltage rating.

One of the smallest designs met with so far measures only 2in × $\frac{3}{4}$in × $2\frac{1}{2}$in high. Table 1 lists the overall dimensions of the six whose electrical performances are given in Section 5.

The provision of moulded enclosures simplifies the question of clearance to the case and earth and contributes to the achievement of the small dimensions quoted.

Table 1

OVERALL DIMENSIONS OF SOME SINGLE-POLE MINIATURE CIRCUIT-BREAKERS

Make	Dimensions		
	Length	Width	Maximum projection
	in	in	in
1	4	$1\frac{7}{8}$	$4\frac{1}{4}$
2	$4\frac{1}{2}$	$1\frac{1}{2}$	$4\frac{3}{4}$
3	$3\frac{3}{4}$	1	3
4	$3\frac{3}{8}$	1	3
5	5	$1\frac{1}{8}$	3
6	$4\frac{3}{4}$	$2\frac{1}{4}$	$3\frac{7}{8}$

(3.3) Electrical Requirements

(3.3.1) On Load.

Currents up to the maximum rating must naturally be carried without overheating and without undue loss.

In order to keep the voltage drop across the contacts to a minimum in service, some rolling and/or wiping action is generally incorporated.

In order to reduce the size of the contacts to a minimum and eliminate skilled fitting, there has been an almost universal tendency to adopt butt contacts, which have been found to give remarkably low losses, e.g. 5 mV at 50 amp. At low ratings, say below 2·5 amp, the loss caused by the overload device, particularly if it is of the electromagnetic type, may absorb a substantial proportion of the supply voltage.

The maximum current rating varies appreciably from one make to another, but lies generally within limits of 25–60 amp, being controlled by the highest permissible temperature rise. B.S. 862 : 1939 rules[3] [Section 13(*b*)] that the temperature rise of the current-carrying parts shall not exceed 30° C, except any operating coil or thermal element that may be used.

(3.3.2) On Overload.

Tripping must be ensured on serious maintained overloads but must not occur on harmless short surges, with particular reference to switching and starting surges. Speedy resetting of any time delay employed may be required on occasions, e.g. when inching motors. The use of time-delay devices is dealt with in some detail in Section 4.

(3.3.3) On Short-Circuit.

On severe overloads and short-circuits tripping must be instantaneous, thereby overriding the operation of the time-delay device. Means for achieving this will also be discussed in Section 4. A definite rule cannot easily be made about the amount of short-circuit protection to be afforded by miniature circuit-breakers, but very few circuits on which they are likely to be used have a prospective short-circuit current exceeding 3–5 kA; furthermore, it is the authors' experience that in the great majority of cases its value lies, in fact, below 1 kA where sub-circuits are concerned. It is no doubt for this reason that in some designs the rupturing capacity has been sacrificed in order to produce a circuit-breaker of very reduced dimensions, such as those applying to the design referred to in Section 3.2.3, such a circuit-breaker being backed up with an h.r.c. fuse if necessary.

The clearing of substantial fault currents leads to the problem of arc disposal; owing to the small amount of space available for arcing, the arc must be got rid of expeditiously, particularly since the contact gap is usually no more than a fraction of an inch. The task of the contact arrangement is thus an arduous one, and assistance is normally obtained from one or more of the following arc-disposal devices:

(*a*) Arc chutes.
(*b*) Blow-outs.
(*c*) Arcing contacts.

Arc chutes make for rapid and effective cooling and extinction of the arc and are essential for d.c. duty. They should be made of a material of good thermal capacity, such as asbestos com-

pounds, and have a large surface resistivity for efficient arc interruption; they may be either fabricated or moulded complete. Great attention has been paid in recent years to the design of arc chutes, which have been found to affect the breaking capacity of contacts more than any other single factor. Generally speaking it is desirable to confine the arc as closely as possible, and at the same time expose to it to the maximum available cooling area. A number of patents have been taken out on various designs of arc chutes. The best known of these, perhaps, is the De-ion type, which tends to split up the arc into small, relatively harmless and more easily extinguished sections.

Blow-outs are used in many instances in order to draw the arc rapidly away from the small contact gap. Since miniature circuit-breakers are primarily designed for a.c. duty, the blow-outs are generally self-excited.

Blow-outs may easily assume large proportions, and in order to save space, various ingenious devices and combinations have been introduced, e.g. a combination of blow-out and short-circuit trip, or a combination of fixed contact and blow-out coil; the latter arrangement completely dispenses with the use of a separate blow-out coil, the fixed contact strip being coiled as shown in Fig. 1, thus providing its own blow-out m.m.f.

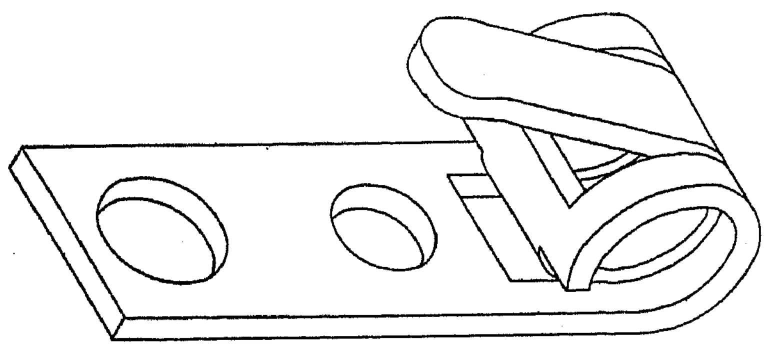

Fig. 1.—Combined blow-out coil and fixed contact.

Arcing contacts have been used in some instances to reproduce the contact operating sequence of the larger circuit-breakers; in addition to the main contacts an arcing contact and a further auxiliary contact may be incorporated. The arcing contact may have a carbon tip to prevent welding, particularly on making fault currents, but this, on the other hand, tends to give a hotter and more damaging arc. Fig. 2 shows an effective combination of these contacts, together with their arc chute.

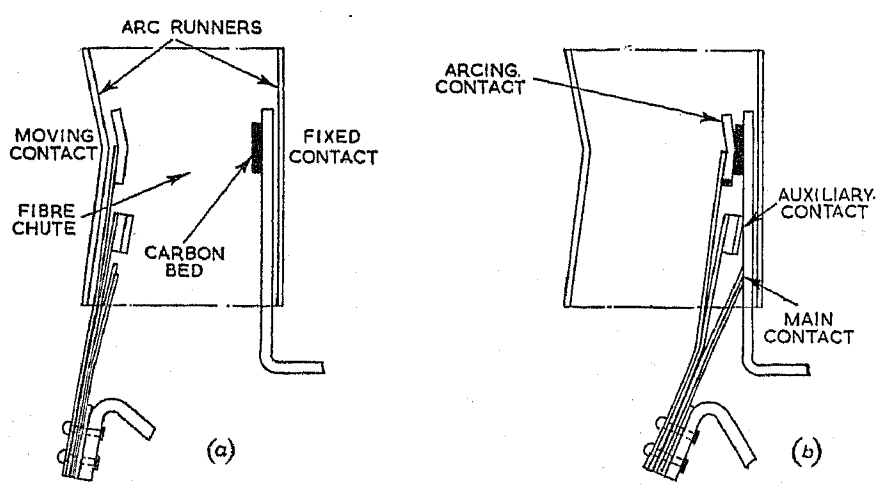

Fig. 2.—Arcing-contact arrangement in a miniature circuit-breaker.

(4) OVERLOAD AND SHORT-CIRCUIT PROTECTION

By virtue of the problem of size, more thought has been given to automatic tripping devices used in miniature circuit-breakers than to any other feature, and a number of designs have been patented.

(4.1) Instantaneous and Time-Delay Operation

The automatic tripping of circuit-breakers may be either instantaneous or delayed.

Instantaneous tripping operates invariably on the electromagnetic principle and is required in all cases to give protection against heavy faults, such as short-circuits. The term "instantaneous" is only relative, used by comparison with an intentional time-delay; in practice there is a definite minimum time-delay, owing to the inertia of the mechanism. This time is usually of the order of 10 millisec and appears to be independent of any particular design. For this reason miniature circuit-breakers have on occasions been referred to as half-cycle circuit-breakers.

In addition to providing the safeguard against short-circuits, instantaneous tripping may be used for ordinary overload operations whenever it is desired to give a close and immediate protection to a circuit or an appliance.

In most cases, however, the provision of some time delay is desirable, and in fact essential, to prevent undesired tripping on harmless short-lived overloads, and in particular to overcome starting and switching surges, which are a feature of practically every circuit, with the exception of heating appliances having a high initial resistance.

The starting surges of motors are well enough known, but it is not generally realized that an even higher, though very short, surge occurs when switching on an incandescent-filament lamp; in fact, its value is of the order of 10–12 times the normal running current, and is clearly shown in Fig. 3. Starting surges of

Fig. 3.—Oscillogram showing switching surge when making circuit containing one 150-watt incandescent-filament lamp.

R.M.S. operating current = 0·65 amp.
Starting current = 9·75 amp.
Duration of surge = 4 millisec.
Resistance = 25 ohms cold; 352 ohms hot.
Experimental surge ratio = 10·7.
Calculated peak ratio = 14.

different intensities occur also with fluorescent and mercury-vapour lamps. Thus a time-delay trip will normally be required for the lower range of overloads, combined with instantaneous operation on short-circuits.

(4.2) Time-Delay Devices

Time-delay devices used with miniature circuit-breakers are either of the thermal, bimetal-strip, type, directly or indirectly heated, or of the electromagnetic type, working on the hydraulic-dashpot principle. The speed of operation of both types is a function of the current: the larger the overload the quicker the action, the result being an inverse time/current characteristic.

(4.2.1) Thermal and Electromagnetic Time-Delays.

Thermal time-delays have the advantage of being simple in design and cheap to manufacture; they may be made to very small dimensions and can be arranged for easy calibration and subsequent adjustment.

Against these points, an electromagnetic time-delay can provide both delay on overload and instantaneous operation on short-circuits, whereas a thermal element cannot give the latter and requires a separate electromagnetic trip for that purpose. It must, however, be added that some ingenious yet simple combinations of thermal time-delay and electromagnetic instantaneous trip have been devised, one of which is shown in Fig. 4;

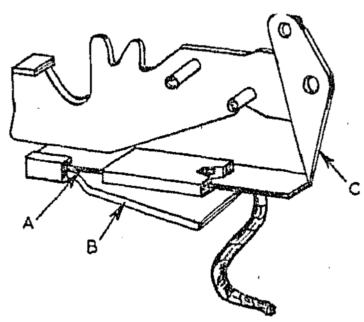

Fig. 4.—Combined bimetal thermal trip and magnetic trip.

on overload, the bimetallic strip A behaves as a thermal time-delay, but on short-circuit it acts as a conductor placed in a magnetic field and is attracted by the magnetic block B.

A considerable drawback of thermal trips is their long re-setting time, which may exceed 1–2min, whereas almost instantaneous resetting of dashpots can be obtained by means of a non-return valve. The use of such a valve will also permit the inching of motors which may be impossible with a thermal device, particularly against a heavy load. In addition, operation of the dashpot can be rendered less dependent on temperature than that of the bimetal strip, provided that a suitable oil with a very flat viscosity/temperature characteristic is used. Silicone fluids have given excellent results for this purpose, comparative curves with ordinary mineral oils being shown in Fig. 5. On

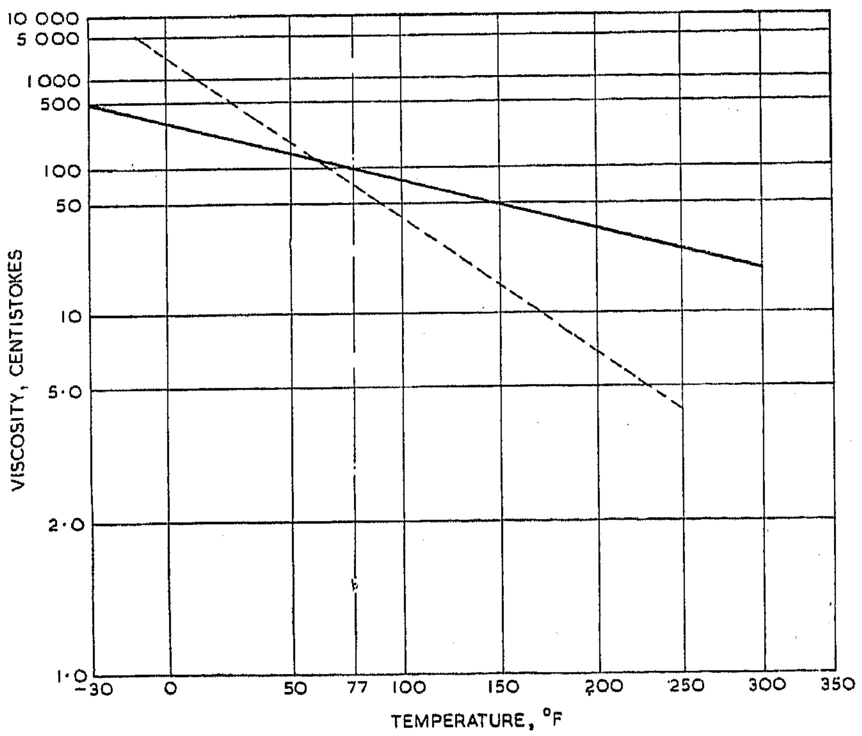

Fig. 5.—Viscosity/temperature characteristics.
——— 100-centistokes silicone fluid.
— — — Petroleum oil.

the other hand, it must be recorded that some designs incorporate features to counteract the ambient-temperature effect of thermal trips, by using a compensating arrangement either for the frame holding the bimetal strip or for the mechanism arm which is released on tripping. This latter case is illustrated in Fig. 4, where C is a temperature-compensating strip.

So far as consistency of operation under a given set of conditions is concerned, there is little to choose between the two types. Electromagnetically operated dashpots, however, have the advantage that they may be built up as sealed units, free from external interference; such an arrangement, which has been specially designed for incorporation in miniature circuit-breakers will now be described, the operation of the more conventional devices being generally well known.

(4.2.2) **Electromagnetically Operated Sealed Time-Delay Units.**

Ordinary hydraulic-dashpot arrangements suffer from the disadvantage that the oil must normally be added *in situ*, and if the correct type is not immediately available the use of the wrong kind may result in a considerably altered time-delay performance. This drawback has been overcome by the use of the closed time-delay unit illustrated in Fig. 6.

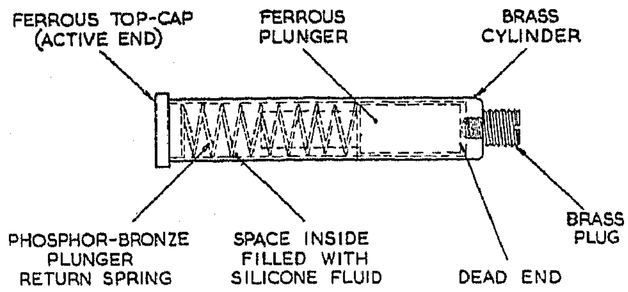

Fig. 6.—Sealed electromagnetic time-delay unit.

It combines the features of a magnetic solenoid core and an oil dashpot, and consists of a hermetically sealed brass cylinder filled with oil, closed at the "active" end by a magnetic cap and at the "dead" end by a brass plug. The cylinder also contains a spring-loaded magnetic plunger, the spring biasing the plunger away from the "active" end.

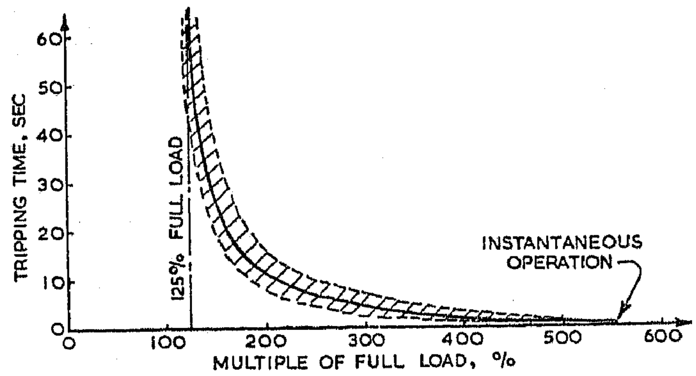

Fig. 7.—Inverse time characteristic for electromagnetic time-delay unit, showing area of operation.

When the m.m.f. of the overload coil surrounding the time-delay unit exceeds a preselected value, the plunger travels towards the magnetic cap, compressing the spring and displacing the oil, tending to take up a central position inside the coil but being stopped by the magnetic cap before so doing. With minimum operating current flowing the design is such that at this instant, but not before, the force of attraction on the external armature becomes sufficiently great to pull it towards the magnetic cap, thereby tripping the mechanism.

When the overload is very large, and particularly during a short-circuit, the force of attraction on the armature, with the plunger still held against the brass end, attains sufficient power to cause instantaneous operation without movement of the plunger. Thus this unit provides instantaneous operation beyond a specified overload level, the ratio between the instantaneous operation current and the rated current being termed the "instantaneous-trip ratio" (Fig. 7).

This ratio may be increased, if desired, by means of an auxiliary coil, as shown in Fig. 8, the effect of which on the instantaneous-trip ratio is clearly seen from Fig. 9. A variation of the auxiliary m.m.f. provides an easy means of altering the opposing force exerted by the auxiliary coil and hence of obtaining different ratios. This arrangement may be particularly useful for motors with high starting-current ratio, such as split-phase types.

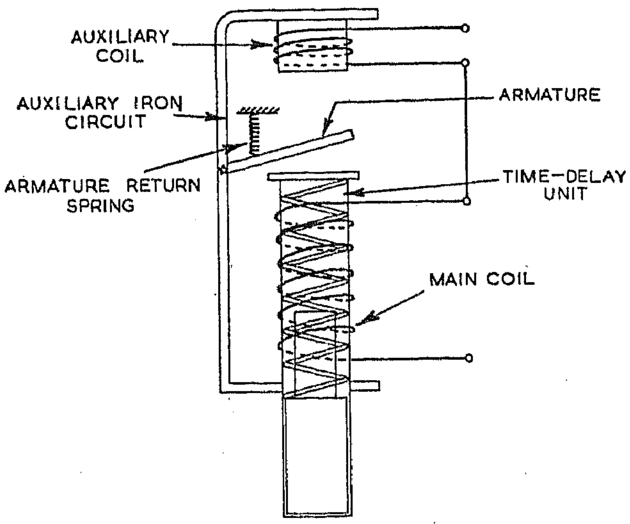

Fig. 8.—Auxiliary-coil arrangement for time-delay unit.

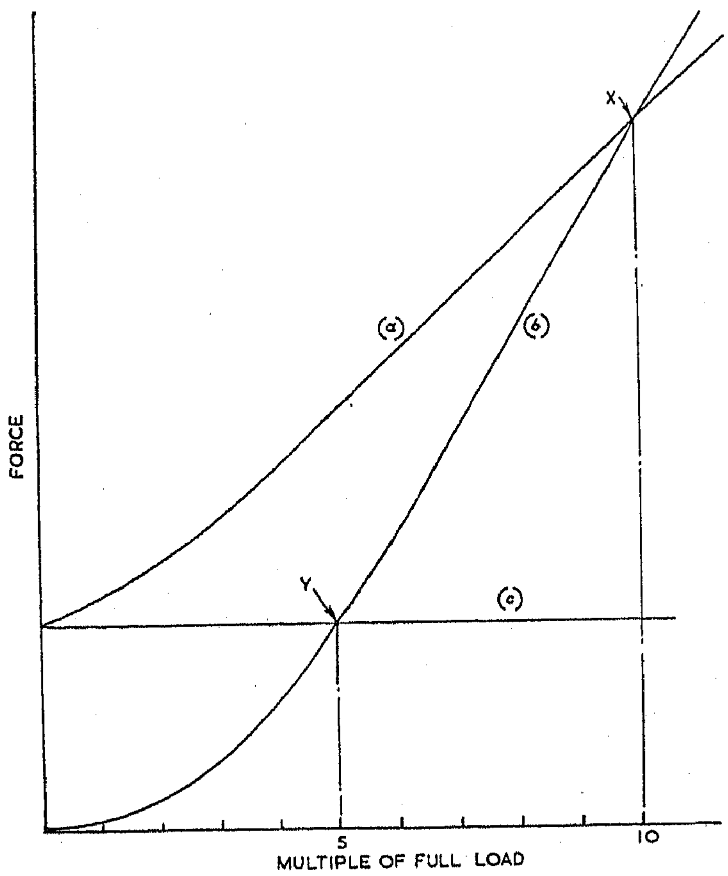

Fig. 9.—Effect of auxiliary coil on instantaneous-trip ratio.

(*a*) Auxiliary-coil force.
(*b*) Overload-coil force with plunger at inactive end.
(*c*) Flapper-spring restoring force.
X. Instantaneous trip with auxiliary coil.
Y. Instantaneous trip without auxiliary coil.

(5) RUPTURING CAPACITY

Of all the points concerning miniature circuit-breakers, rupturing capacity is perhaps the most controversial and the one of greatest technical interest to engineers and users. The exact rupturing capacity can be considerably affected by even small details of design, particularly where contacts, arc chute, and blow-out are concerned, and it is therefore difficult to quote precise values.

(5.1) Criterion of Satisfactory Performance

In addition, it is necessary to provide some criterion—rather different from that for large circuit-breakers—which clearly states when a test result may be considered satisfactory. After the clearing of a fault, one would not be expected to have to examine the circuit-breaker and possibly to replace some parts, e.g. a contact or an arc chute, which procedure is quite usual after a severe fault has been cleared by a large circuit-breaker. Miniature circuit-breakers are liable to be installed in remote places, where no technician may be immediately available, and they are expected to deal repeatedly, if not frequently, with the maximum fault conditions likely to occur without coming to any undue harm. In this connection it must be borne in mind that they are not usually designed for easy replacement of parts, for economic reasons, a complete renewal being deemed preferable in the case of damage.

Thus it appears that two values have to be considered, the actual rupturing capacity and the useful rupturing capacity, which is likely to be appreciably lower than the former.

A sound criterion for ascertaining the useful rupturing capacity will be found in the Australian Specification for miniature over-current circuit-breakers,[2] which states that "throughout the breaking-capacity test the operating handle and all openings in the enclosing case shall be surrounded with loose, dry, cotton waste . . ." which waste must not ignite during the tests [Section 20(*d*)]. This criterion will be found considerably more severe than the more usual one of "blowing the earth fuse" (connected to a metal case or to a wire mesh surrounding a case of insulating material), and is a fairly reliable guide to the useful rupturing capacity. Tests have shown that this cotton waste usually ignites when testing at the actual rupturing capacity, whereas the earth fuse may well remain intact.

(5.2) Breaking Capacity

As a rough guide it may be taken that the maximum current that can be effectively broken varies inversely as the square of the voltage, so that the apparent power then varies inversely as the voltage, assuming all other conditions to remain the same.

Table 2

A.C. BREAKING CAPACITY OF SOME MINIATURE CIRCUIT-BREAKERS

Make	Makers' rating	Test voltage	R.M.S. breaking capacity	
			Prospective current	Apparent power
	volts	volts	kA	MVA
1	500	250	3	0·75
2	250	230	4	1·0
3	125	125	5	0·625
4	125	125	5	0·625
5	500	250	4	1·0
6	250	250	6	1·5

Table 2 gives the approximate maximum breaking capacity of the six makes listed in Table 1, at the appropriate phase-to-neutral voltage; this is likely to yield the fairest comparison, for it is being held that single-pole breakers are primarily intended for such a duty.

Thus it may be taken as a general guide that the maximum a.c. rupturing capacity of existing designs is of the order of 1 MVA per pole per phase. Currents considerably in excess of these figures may be interrupted, but not usually without some damage to the circuit-breaker. Fig. 10(*a*) shows such a result, in which two circuit-breakers in series cleared a prospective r.m.s. current of 10 kA at 440 volts a.c.

The figure quoted in the Table will hold good down to power factors of about 0·5, beyond which the damage through repeated fault operation may become rather serious. It is unlikely that a miniature circuit-breaker will clear its maximum rupturing capacity more than, say, 3–6 times without appreciable reduction in its efficiency.

The speed of clearing these high currents is limited principally

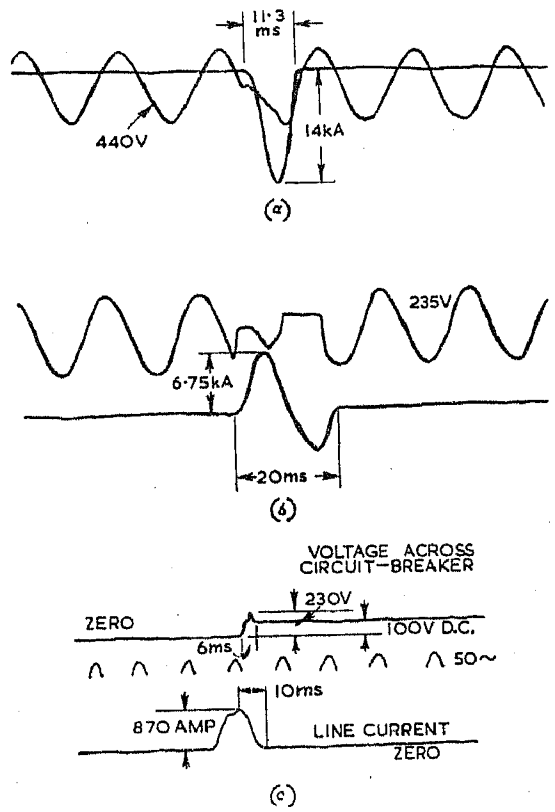

Fig. 10.—Oscillograms of some short-circuit tests on single-pole miniature circuit-breakers.

Oscillogram	Prospective current	Test voltage	Power factor	Remarks
	kA	volts		
(a)	10	440, a.c.	0·65 lagging	2 in series
(b)	4	235, a.c.	0·25 lagging	
(c)	0·8	110, d.c.	—	Non-inductive load

by the definite minimum time of the mechanism and overload device as discussed in Section 4, being of the order of 10 millisec down to the power factor stated. Consequently the breaking capacity of a given design is independent of the particular current rating tested, provided that the overload coil or bimetal strip for the lower ratings can withstand the effects of the fault surge.

The useful breaking capacity depends, of course, on the criterion of satisfactory behaviour required, but will be substantially lower, say one-half to one-quarter of the values quoted, under which conditions a fault may be cleared perhaps 50–100 times without ill-effects to the operating efficiency. Such breaking capacities may be considered as rather low, but this is not really serious, since it will be found that the prospective short-circuit current in the great majority of applications lies considerably below even these figures (see Section 3.2.3).

In this connection it should be mentioned that for the lower current ratings the actual short-circuit current will be effectively limited by the impedance (or resistance) of the overload device. Thus for the 5 and 2·5-amp ratings of a particular design incorporating an electromagnetic time delay, the prospective current at 250 volts (a.c. or d.c.) would be limited approximately to 2 500 and 750 amp respectively.

Table 3 gives extracts from a series of breaking tests carried out by an independent testing authority.

These tests were rather severe because of the low power factor, but they are thought to illustrate well this difference between the actual and useful breaking capacities. The oscillogram for the second test is shown in Fig. 10(*b*).

On a d.c. supply the breaking capacity will normally be appreciably less than on an a.c. supply, and for a given voltage may be expected to be a quarter of the a.c. value or even less. In order to compensate for this it is common practice to reduce

Table 3

EXTRACT FROM TEST REPORT ON BREAKING CAPACITY

Test voltage (a.c.)	Prospective r.m.s. current	Power factor (lagging)	Observation at time of test	Observation after test
volts	kA			
235	2	0·20	Slight noise and flash.	Contacts slightly burnt.
235	4	0·25	Slight noise and flame which persisted for about 5 sec after test.	Contacts badly burnt.

the direct-voltage rating, usually to half the alternating value. The operating time, however, still remains about 10 millisec, as shown in Fig. 10(*c*).

(5.3) Making Capacity

The making capacity of a miniature circuit-breaker referred to the prospective r.m.s. current is likely to be somewhat lower than its maximum breaking capacity, and may be taken to have about the same value as the useful breaking capacity discussed above. The reason for this difference lies mainly in the absence of contact pressure on making. This pressure is the principal mechanical force opening the contacts on tripping from the closed position, the main mechanism spring being only a secondary agent. On making, however, the latter is the only mechanical opening force, with a consequent slowing down of contact separation, delay in arc interruption and worsening in performance.

A further point accounting for this reduced making capacity is the absence of contact wipe which will normally take place on complete closing or opening, with a consequent risk of contact welding taking place on making a fault. This can be overcome by using a carbon-tipped arcing contact, although this will result in a fiercer and more damaging arc. Alternatively, copper-tungsten or silver-tungsten contacts have been found to have excellent erosion-resisting and anti-welding properties, but when used as single main contacts (as distinct from separate arcing contacts) will reduce the maximum current rating by virtue of their lower electrical conductivity.

(5.4) Scope for Short-Circuit Protection

It is of interest to note that the values quoted in Table 2 appreciably exceed the capacity stipulated in B.S. 936, Table 4, for circuit-breakers up to 60 amp; they surpass, in fact, the value for the 100-amp rating, being approximately equivalent to that for the 200-amp rating.[5]

It has already been pointed out that prospective fault currents exceeding the capacity of miniature circuit-breakers are the exception rather than the rule in sub-circuits. In the event of such large faults occurring, however, satisfactory protection may be obtained by the use of an additional back-up h.r.c. fuse of higher rating. This combination can be made to ensure that the fuse comes into action only when the fault current approaches the capacity of the circuit-breaker, which will discriminate against the fuse below this critical value.

(6) APPLICATION

In order to appreciate to the full the advantages to be gained in the application of miniature circuit-breakers, some brief comparison is necessary between their operational features and those of fuses.

(6.1) Tripping and Fusing Characteristics

Fuses designed in accordance with B.S. 88 : 1952 fall into one of the three classes. The specification provides that Class-P fuses shall have a maximum fusing factor of 1·25, Class-Q fuses a factor of 1·75 for h.r.c. and of 2 for rewireable types, and Class-R fuses may have fusing factors above these figures. When subjected to the minimum fusing current these fuses must blow within a time which varies from 45 min to 8 hours according to class and rating. Therefore the time delay of a fuse at minimum fusing current is rarely shorter than 45 min and can vary enormously.

Characteristics of miniature circuit-breakers with electromagnetic and thermal-magnetic trip units are compared in Fig. 11 with those of Class-Q fuses. It can be seen that in the

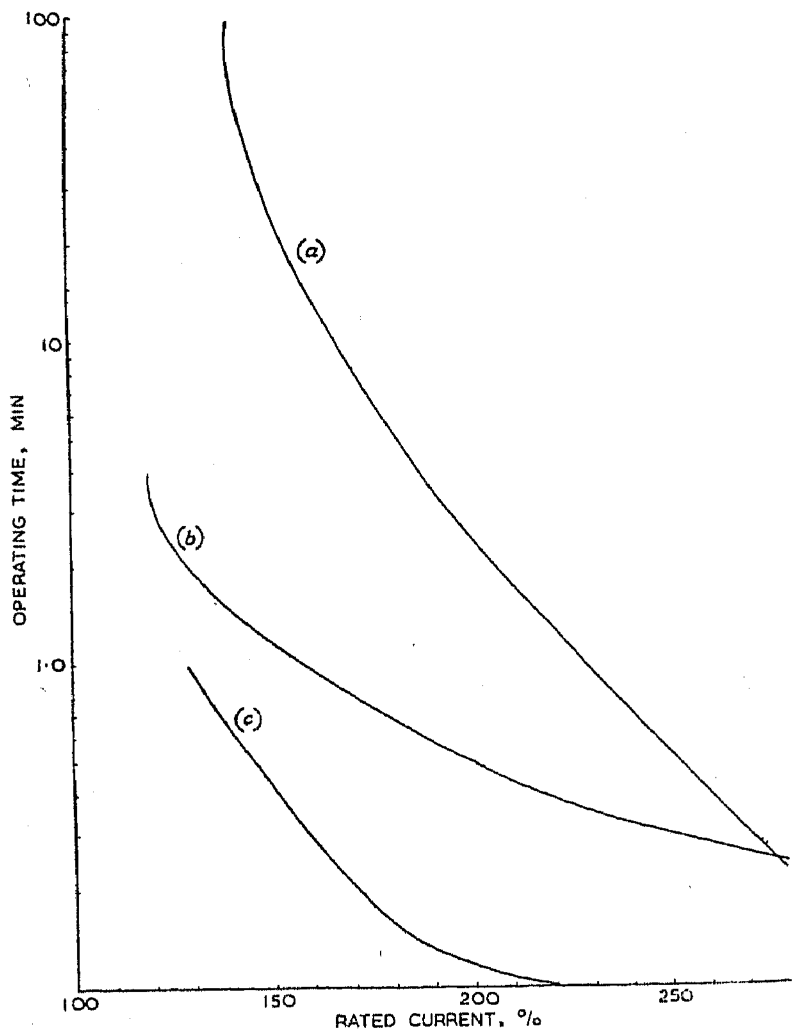

Fig. 11.—Protective characteristics in region of minimum fusing current.

(a) Class-Q h.r.c. fuses.
(b) Miniature circuit-breaker with thermal delay.
(c) Miniature circuit-breaker with electromagnetic delay.

region of minimum fusing currents, the circuit-breaker time delays, and particularly the electromagnetic delays, are very much shorter (and, it may be added, more consistent). Consequently, a far more accurate degree of protection is obtainable.

(6.2) Safety and Misuse

A rewireable fuse is subject to misuse inasmuch as the careless or amateur electrician might easily wire it with an element of far greater section than is safe. Cartridge fuses, particularly in the lower ratings, are often used, not because of their higher rupturing capacity, but because they are not open to this abuse and give a closer measure of protection.

A properly designed and sealed circuit-breaker overcomes danger of misuse inasmuch that, once it has interrupted the circuit, the circuit cannot be reinstated if the fault conditions continue.

(6.3) The Miniature Circuit-Breaker as an Alternative to the Fuse

Since the war the use of small circuit-breakers has spread with surprising rapidity. Applications have ranged from generator control panels to house service units, and from ship circuits to street lighting, while many of the stringent and accurate requirements of motor protection have been met. They have also been used on housing estates abroad to limit the current which can be taken by occupiers of houses where electricity is supplied on a simple rental basis. The resultant experience gained both by manufacturers and users is leading to their still wider adoption.

Their size is such that they may be used in any instance where fused switches or switch-fuses of cartridge or rewireable type would previously have been used, and such substitution is always technically correct, providing that

(a) The possible fault obtainable is less than the rupturing capacity of the breaker, or suitable backing protective devices are installed.
(b) The time delay is adequate to maintain the circuit during temporary surges.

When considering the application of multi-pole miniature circuit-breakers the points mentioned above concerning rupturing capacities and tripping characteristics assume even greater importance. This is because there is more likelihood in multipole circuits of other devices, e.g. motor starters, being provided between the circuit-breaker and the apparatus it protects.

Under these conditions fuses are really unsuitable. On the one hand, a sensitive h.r.c. fuse of small current rating is likely to blow on the occurrence of a fault before the circuit-breaker could open the circuit, thereby preventing quick reinstatement of supply. On the other hand, a slow-acting rewireable fuse would be easily beaten by the circuit-breaker so that its presence would serve no useful purpose.

With the exception of motor-starter equipment, the branch circuits of a supply controlled by a triple-pole circuit-breaker should themselves be controlled by circuit-breakers of similar characteristics but smaller rating. It follows that the smaller the percentage of fuses in an installation the greater the saving in maintenance and the greater the degree of convenience. In fact, the complete circuit-breaker scheme is in this respect the ideal.

It is interesting to compare the respective sizes of two distribution boards having eight 50-amp triple-pole-and-neutral outgoing ways, each way having means for protection and isolation. If switch-fuses were used the dimensions of a typical arrangement would be 7 in × 36 in × 48 in, weight 168 lb, while the size of a similar board incorporating small circuit-breakers would be 5 in × 23 in × 16 in, weight 55 lb. The difference in size and weight are so considerable that the switch-fuse board would normally require an angle-iron framework for its support, while the circuit-breaker board could be conveniently mounted on a wall. General indications are that they provide far lighter and more compact gear in such arrangements.

There are special considerations in the d.c. use of small double-pole circuit-breakers in ships, where every branch circuit is provided with means for protection and isolation. Hitherto it has been the custom to achieve this through the use of double-pole switches and fuses. It is thought that, in view of the vast number of such branch-circuits in each ship, circuit-breakers can provide physical and electrical improvement. Already they have been used on an experimental scale for this work.

(6.4) Distribution

Experience of the advantages of single- and multi-pole miniature circuit-breakers has recently been followed by their use in distribution schemes, and several smaller installations have

already been carried out. One of these relating to a new school and employing circuit-breakers exclusively is shown in Fig. 12. Such schemes will provide a far clearer appreciation of their value and will lead to their more general adoption.

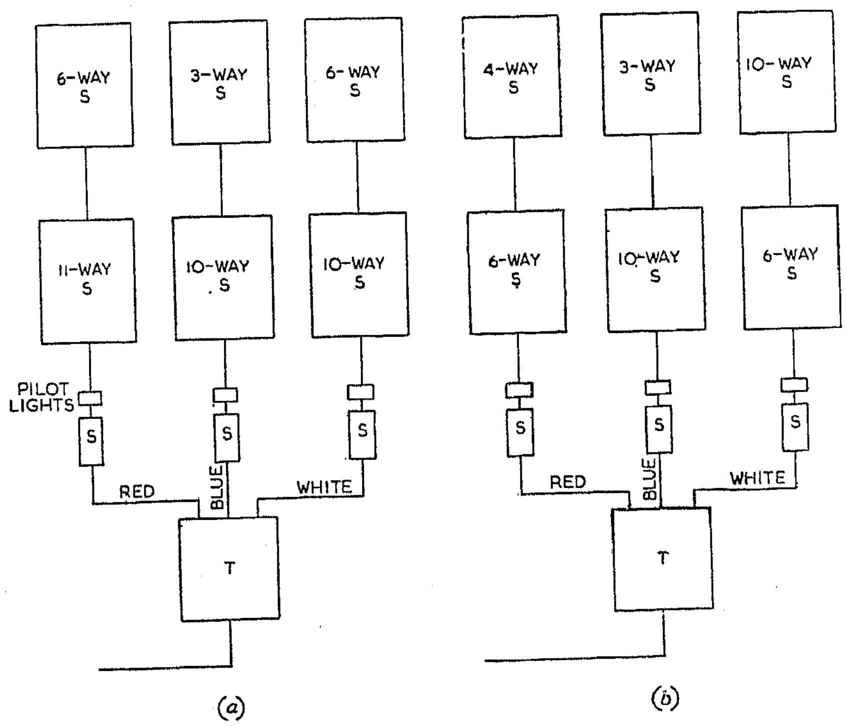

Fig. 12.—Block schematic of distribution scheme using miniature circuit-breakers.

S. Single-pole-and-neutral type.
T. Triple-pole-and-neutral type.

(*a*) Lighting circuits.
(*b*) Heating circuits.

In many of the larger distribution schemes of conventional design opportunities exist for their application instead of both switches and fuses. Often a bank of switches or a switched fuseboard is employed to control the lighting in a large room or office. The use of circuit-breakers in such instances provides an obviously more suitable arrangement.

The advantages in leaving the final sub-circuit control and protection safely in the hands of the electrically unskilled have been readily appreciated in the United States. Panelboards incorporating circuit-breakers are used extensively and this has naturally had its effect upon distribution layouts. The equipment is more often conveniently placed and consequently more readily accessible than in Britain, where considerable expense may be incurred in keeping the equivalent equipment out of harm's way.

(6.5) Domestic Applications

A domestic installation is almost invariably in the hands of either an unskilled householder or, what is worse, an amateur electrician. Some people are afraid of a fuseboard, and in relying upon outside help for the replacement of fuses may well be compelled to wait for a day or so before a circuit can be re-employed.

Miniature circuit-breakers are ideally adapted for use in domestic installations, and as has been shown in other countries, when designed for that purpose quickly gain the ascendancy over switches and fuses of the domestic type.

So far, development in Britain has been directed towards the production of small general-purpose circuit-breakers which are technically suitable for wide fields of application. These, while being completely adequate for use in domestic circuits, are expensive for this purpose, and it is not expected that this field can be adequately catered for until circuit-breakers of cheaper design are produced.

(7) ECONOMY OF MINIATURE CIRCUIT-BREAKERS

(7.1) The Cost of Circuit Reinstatement

The simplicity and speed with which a circuit may be reinstated at negligible cost by the use of miniature circuit-breakers are of great economic significance. In this regard they contrast very favourably indeed with fuses, whether of the rewireable or the cartridge type.

Efforts have been made to obtain dependable figures of the proportion of fuses expended per annum to the number of fuses installed, but without success. Few of the undertakings approached keep records on this point, and such information as has been obtained varies so greatly from user to user that it cannot be regarded as accurate. The fact remains, however, that the manufacture of fuse wire and fuse cartridges finds employment for a comparatively large industry in Britain, and it is reasonable to suppose that only a proportion of the products of that industry are devoted to new installations.

In the most highly industrialized countries the cost of fuse-element replacements is regarded as unnecessarily high. The distance between a blown fuse and the electrician makes for very inefficient use of labour. Although skilled labour is becoming increasingly expensive, the use of unskilled labour may lead to more costly results or even danger to life.

As an illustration, when a fuse blew in an operating theatre in a large London hospital, the location of the nearest electrician, his tools and fuseboard were such that it took 50 min to reinstate the circuit.

Not only is there frequent difficulty in determining exactly which fuse has blown, but there is a very widespread habit of replacement before the faulty circuit has been checked. Although this is a quick and satisfactory procedure in dealing with a transient fault, one of a more persistent nature is apt to be expensive. For example, the cost of a 30-amp 500-volt h.r.c. fuse is about 3s. and an electrician is paid at the rate of nearly 4s. per hour.

An immediate attempt to reinstate a circuit protected by a miniature circuit-breaker can be made in perfect safety, at negligible cost, and its success or failure indicates whether or not the circuit requires the attention of a skilled man.

(7.2) Initial and Maintenance Costs

In order to make any economic comparison between miniature circuit-breakers and equivalent gear in particular applications there are three obvious but important questions to be answered:

(*a*) Will circuit-breakers make initial costs greater or less?
(*b*) If the answer is greater, will savings of maintenance cover the difference?
(*c*) How severely will production losses due to stoppages affect the issue?

Question (*a*) is easily answered in any particular instance. Table 4 shows some comparative costs based on the price of a typical 15-amp single-pole-and-neutral switch-fuse.

Question (*b*) is not easily answered, since both the frequency of fuse replacement and the associated cost cannot be estimated accurately and it is impossible even to suggest figures which would be applicable generally, although it would be comparatively simple to obtain data from installations where records are kept. The frequency of fuse replacement would be affected, for instance, by such diverse factors as atmospheric conditions, types of apparatus to be protected and the state of the wiring installation; while the cost of each replacement would depend to a large extent on the availability of skilled labour to reinstate the circuit.

An investigation into the number of fuses that have blown in a new and well-known public building in London has revealed some surprising information. The installation contains nearly

Table 4

SOME BRITISH SWITCH-FUSE AND MINIATURE-CIRCUIT-BREAKER PRICE COMPARISONS

Current rating	Pole arrangement	Relative costs	
		Switch-fuse	M.C.B.
amp			
15	S.P.N.	100	158
30	S.P.N.	190	158
	T.P.N.	268	568
50	S.P.N.	386	165
	T.P.N.	558	593

200 distribution boards catering for some 2 000 fused outgoing circuits rated between 15 and 60 amp. In the first 27 months of use 462 fuses were expended in this part of the installation, and in no instance was there found to be anything more than a transient fault. It will be readily appreciated that these figures represent a very considerable cost both in labour and material.

Regarding question (*c*), the cost of loss of production may well be considerable. If the fuse protecting a machine which is producing at the rate of £200 per hour were to blow, and it took a quarter of an hour to reinstate the circuit, loss of production would be £50. In such a situation this consideration would outweigh all others. It is well known that very many fuses blow without any apparent cause. In such cases, if protection is by means of miniature circuit-breakers, the cost of reinstatement is the cost of the very short time spent by the actual user of the circuit in reclosing the circuit-breaker.

(7.3) Some Comparative Costs for Distribution

The large variations in price and quality of distribution fuse-boards makes it difficult to present a clear yet comprehensive comparison. Table 5 shows the price relationship between two types of h.r.c. fuse distribution boards on the one hand and circuit-breaker distribution boards on the other.

Table 5

RELATIVE COSTS OF FUSES AND MINIATURE-CIRCUIT-BREAKER DISTRIBUTION BOARDS

Type of distribution board	Relative costs		
	6-way S.P.N. 15-way	6-way T.P.N.	
		30-amp way	50-amp way
Fuse type 1 ..	100	240	320
Fuse type 2 ..	180	600	880
M.C.B.	184*–306	725	825

* This figure represents the price of a recently designed miniature circuit-breaker of maximum rating 15 amp at 250 volts.

Although limited in extent, this Table represents a fairly general picture; it gives, of course, initial prices only and takes no account of the inherent advantages of the circuit-breaker in maintenance.

The relative costs of American fuse and circuit-breaker equipment are interesting in this respect. Table 6 gives some indication that circuit-breakers are by no means initially competitive in that country. Even so, they have already been found economical at initial prices far more favourable to fuses than those in Britain to-day. The popularity of the circuit-breaker installation is spreading in an ever-increasing number of countries after a wide experience of fuses at respective price differences similar to those in the United States.

Table 6

RELATIVE COSTS OF FUSE, SWITCH-FUSE AND CIRCUIT-BREAKER PANEL BOARDS IN THE UNITED STATES

Number of ways	Relative costs		
	Fuse	Switch-fuse	M.C.B.
4	100	202	211–229
16	151	357	373–460
20	169	408	404–536
32	355	560	624–767
40	408	660	686–920

(8) CONCLUSIONS

The paper has endeavoured to present a general survey of miniature circuit-breakers, particularly as used in Britain, in view of the growing interest shown in their use during recent years.

It has been seen that their design presents its own problems and difficulties, which may differ appreciably from those relating to ordinary circuit-breakers, by virtue of their double function of switch and circuit-breaker. In this connection it is felt that the issue of a British Standard on the lines of the Australian Specification[2] would be of considerable benefit. Already the Electrical Engineering Department of Lloyd's Register of Shipping has found it necessary to issue some rules regarding the use of miniature circuit-breakers.[6]

It is felt that there is scope for the development of small circuit-breakers for particular applications. On the other hand, moulded-case circuit-breakers of larger current rating would have great effect in Britain on the compactness of electrical equipment. It is to be expected that, the more widespread the adoption of miniature circuit-breakers generally, the more far-reaching will be the effects on maintenance costs, and it seems more than likely that they will occupy a place of constantly increasing importance in the field of small electrical protective switchgear.

In this respect it is worth recalling that, until about 1930, electrical protective practice was very similar in the three major exporting countries of electrical switchgear, the United States, Germany and Britain. Thereafter, however, a most marked divergence has appeared. In the United States, moulded-case circuit-breakers have ousted most fuses; in Germany, too, miniature circuit-breakers are being used on a large scale. Yet in Britain, fuses have on the whole kept the field. Most countries have followed the lead of the United States and Germany, with the result that Britain, by continually championing the fuse, has fallen out of step and thereby lost valuable opportunities. Until a satisfactory range of miniature circuit-breakers is soundly established, Britain will suffer a loss, for experience has shown that once users have adopted miniature circuit-breakers they are unlikely to go back to the older forms of protective device.

(9) ACKNOWLEDGMENTS

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They further wish to acknowledge the advice given by Mr. R. Speirs, Southern Manager of the Dorman Smith Group of Companies, in the preparation of the paper.

Thanks are also due to Mr. G. Holden, Borough Engineer of Halifax, for permission to use, and to Mr. J. Tattley for help in supplying, the information contained in Fig. 12.

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DISCUSSION BEFORE THE UTILIZATION SECTION, 20TH JANUARY, 1955

Mr. H. W. Swann: I first saw distribution assemblies of miniature circuit-breakers in this country as far back as 1925 at a German-owned factory in Doncaster, and at that time the users regarded them as very satisfactory.

I have read the paper principally in connection with The Institution's Wiring Regulations 611 and 612 (C), because the terms of those Regulations are, I think, dictated by the inherent characteristics of fuses. Regulation 612 (C) says that the fuse rating shall not exceed that of the circuit it controls, and thus in Regulation 611 the operating current of circuit-breakers is specified to match a fuse possessing a fusing factor of two by saying that the circuit-breaker shall be set to operate at up to twice the circuit rating. I have always thought this tends to rob the circuit-breaker of its inherent ability to afford closer control of overload. We know that some fuses may take a long time to operate at values just above that represented by their fusing factor, and if the circuit is designed with a margin to allow for this, the extra copper is in a sense wasted. If it is unwise to subject a circuit to more than its rated current, the use of a circuit-breaker set to operate just above this rating obviates the need for a margin and would prevent damage where no margin exists. Are the authors prepared to recommend an amendment to Regulation 611?

In Section 5 the authors say that, if the circuit-breakers are called upon to operate well above their breaking capacity, some damage may result. This involves the question of maintenance service, because most consumers would always close the circuit-breaker again, and if the contacts were damaged overheating might result, which might lead to spluttering at the contacts. In view of this, do the authors think the insulation of one circuit-breaker from its neighbour in a multiple assembly is sufficiently secured by its design, remembering that, when a circuit-breaker opens, full voltage appears across the break and thus between one contact and that on an adjacent breaker?

I find Fig. 12 of interest because I imagine it introduces time and current grading—two things which are sometimes difficult to achieve successfully. Will the authors comment on the possibilities of a mixed scheme involving both circuit-breakers and fuses, e.g. where a circuit-breaker controls a ring main with fused socket-outlets? I should also be interested in their comments on a mixture of circuit-breakers with both h.r.c. and rewireable fuses, because this is the kind of installation we may conceivably get.

Mr. E. Jacks: In implying that miniature circuit-breakers have universal application, the authors have been in some danger of overstatement and have made comparisons with fuses and put forward arguments, particularly with reference to American practice, which are not entirely valid. They state, for instance, that in the United States moulded-case circuit-breakers have ousted most fuses, whereas there are more fuses than miniature circuit-breakers used in America. They further state that "we in Britain have fallen out of step and thereby lost valuable opportunities." This I consider to be an incorrect assessment, and the position as I see it is this. The Americans produced enclosed-type fuses some 40 years ago, and while they are an improvement on the fuses previously used, they in no way compare with British h.r.c. fuses. At an early stage in the development of their fuses the Americans standardized the dimensions, and this acted as a deterrent to further improvements. Consequently, when, as the authors state, in about 1930 the Americans produced miniature circuit-breakers, these found a market not only for use on circuits for which they were essentially suitable, but also for circuits where h.r.c. fuses would have been used had they been available. Here, as elsewhere, fault levels continue to increase, and in America the difficulties now being experienced with miniature circuit-breakers have caused American engineers to look with interest at h.r.c. fuses.

It is paradoxical that while American engineers are displaying increasing interest in h.r.c. fuses—for which, incidentally, they have not as yet produced a standard specification—the authors should tell us that we are lagging behind. In this country both h.r.c. fuses and miniature circuit-breakers have been available for more than 20 years, and British engineers have been able to select the protective equipment they considered most suitable for the circuits to be protected. I believe that both h.r.c. fuses and miniature circuit-breakers have their uses and for some applications are complementary to each other.

The authors have gone a long way to prove the case for the use of miniature circuit-breakers where light overload protection is required, but I cannot feel as optimistic as they do about the capabilities of miniature circuit-breakers to cope with short-circuit faults at the fault levels which we know to exist to-day. I am certain that on the majority of industrial circuits 1 MVA is not sufficient. While it is true that faults of high magnitude do not occur frequently, they occur nevertheless, and protection must be provided. For domestic installations, it should be remembered that distribution practice in this country differs from that in the United States, and that here if close to a sub-station it is possible to obtain short-circuit currents of many times the figures the authors have given for the capabilities of even the best miniature circuit-breaker.

Dr. H. D. Einhorn: In South Africa miniature circuit-breakers

are installed extensively and in increasing numbers. Most of them are locally made to an American pattern with a rated rupturing capacity of about 5kA at 230 volts.

A dilemma, however, arises in installations fed from a transformer of more than 200kVA rating or from a large urban underground supply system. The short-circuit rating of any equipment placed on the main distribution board should in these cases exceed 5kA. On the sub-distribution boards, on the other hand, we should like to see the miniature circuit-breaker, on account of its convenience; it can be safely used for the sub-circuits, since short-circuits at the load end are limited by coil and conductor impedances.

One of the author's recommendations may meet this case—"the use of additional back-up by h.r.c. fuses of higher rating." I agree that a mains distribution board with h.r.c. fuse-switches which protect the mains cables and the distribution boards themselves, together with miniature circuit-breakers on the sub-circuit boards for the protection of the final load circuits, would form a very attractive combination, if it were not for the difficulty of obtaining discrimination.

The authors say, "This combination can be made to ensure that the fuse comes into action only when the fault current approaches the capacity of the circuit-breaker, which will discriminate against the fuse below this critical value." Experiments carried out at the University of Cape Town indicate that this mode of operation is not easily achieved, unless the fuse rating is exceptionally high, and thus too high for the most common sizes of sub-main cable.

To be more explicit, discrimination is satisfactory as a rule for small overloads, and the miniature circuit-breaker will trip alone. But the cross-over value of the characteristics, where the fuse blows before the miniature circuit-breaker has cleared the fault, occurs at relatively low currents, which depend, of course on the fuse rating. In most of the tests which we carried out with British h.r.c. fuses and the local circuit-breakers mentioned, discrimination ceased far below the breaking capacity of the latter; in fact, in a range where one would expect short-circuit currents to be quite frequent.

This difficulty has also been experienced in practice, and the compromise usually resorted to is the use of rewireable fuses, say, on the mains board and miniature circuit-breakers on the sub-distribution boards. This sometimes means trusting to luck and the fortunate fact that distribution-board faults are very rare. It also means that there is the possibility of later abuse by the insertion of unduly heavy fuses to force discrimination. The proposal to back up miniature circuit-breakers by h.r.c. fuses seems to be sounder, but it would require either a faster circuit-breaker or slower fuses than tested by us.

It has been mentioned before that miniature circuit-breakers, like any others, break at the current zero. Therefore it needs anything up to half a cycle to clear the fault. The onus thus rests on the fuse manufacturer to provide a fuse which will withstand short-circuit currents of the order of 2kA for at least 0·01sec. At the same time the fuse must have a low enough long-time current rating to protect the mains cables, which are usually of the order of 30–150amp. Here is an opportunity for the h.r.c. fuse manufacturer to provide something which I so far have not been able to find on the market.

The alternative, of course, is the exclusive use of circuit-breakers, but when we want to use the circuit-breaker for the mains board, where the load current is of the order of 100amp and the rupturing capacity varies from 10 to 50MVA, we can hardly expect a miniature circuit-breaker to do the job. If any manufacturer is able to develop a circuit-breaker with oil-circuit-breaker performance at a miniature-circuit-breaker price, he can look forward to a flourishing export market.

Mr. S. Flax: It is perhaps natural that the authors should have concentrated their paper on the single-pole circuit-breaker, although they have mentioned the multi-pole circuit-breaker in one or two places. This might in itself give the wrong impression that the triple-pole miniature circuit-breaker for industrial use had not been developed to the same extent as its single-pole counterpart, which is untrue.

The triple-pole circuit-breaker on a small base has been used in this country for industrial purposes such as machine tools, printing machinery and other applications for at least 25 years. Since the early 1930's it has been used—and this is an interesting application—to protect the hand-held coal-drilling machines employed underground in our collieries. Some 10 000–15 000 of these machines must be working every day in pits in this country at the present time, and a very large number of them are controlled and protected by the small triple-pole circuit-breaker. The duty is quite severe. The normal full-load current is about 10amp, although on low voltage, the starting current is 30–40amp and the machines are started perhaps two or three times every minute throughout the whole shift, which lasts for several hours. It will be obvious how useful a circuit-breaker is in these circumstances. The drilling machines are very liable to be overloaded by the miner, and if a fuse blows in the pit, no unauthorized person is permitted to replace it. The electrician must be called, possibly from the surface, and may have to crawl half-a-mile or a mile to the point where the starting equipment is situated, and there may result a loss of production for 3–4 hours. The use of the triple-pole circuit-breaker has completely eliminated this trouble.

Moreover, when the triple-pole circuit-breaker is used, it is very easy to employ earth-leakage protection merely by the addition of the earth-leakage coil. That is done very frequently, and, in fact, it is used with the circuit-breakers for the mining application I have just mentioned.

More recently, these circuit-breakers have been employed in conjunction with the current-balance type of earth-leakage protection, and many people are beginning to realize that this type of protection can with advantage be applied to smaller circuits than has hitherto been usual. It opens up an entirely new field of protection of personnel and machinery in factories, and the use of the miniature circuit-breaker is helping to bring this type of protection into effective use.

Mr. J. A. Robbins: I feel that the authors have tended to concentrate on showing that in some ways a single-pole circuit-breaker is a better fuse than either a rewireable fuse or a cartridge fuse. I agree that the operating characteristics in the minimum-fusing-current region are much superior to those of fuses, and this fact is tacitly admitted in The Institution's Wiring Regulations, which, subject to overriding considerations of voltage drop, permit the use of smaller cables for sub-circuits protected by circuit-breakers.

However, this does not give the full picture so far as operating conditions on normal installations are concerned. We all know that fuses can normally be relied upon to give protection against line-to-line faults or line-to-neutral faults, but they do not give reliable protection against earth leakage. In many installations in this country a fuse will not even blow on a dead earth fault. Yet it is very easy to combine both core-balance or earth-leakage protection with a miniature circuit-breaker. Hence the superior overload characteristics of miniature circuit-breakers may be combined with shock-risk, fire-risk and short-circuit protection in one relatively small unit.

As a result, there is in my experience a steadily growing tendency in this country to use miniature circuit-breakers with associated earth-fault protection as master circuit-breakers on either main circuits or main sub-circuits. From that the

logical step forward surely is to use miniature circuit-breakers for small sub-circuit protection.

A further advantage of circuit-breakers is that the additional features, such as under-voltage release, remote tripping or auxiliary alarm contacts, which may be incorporated in the mechanism, allow the installation engineer greater flexibility in application. On 3-phase applications a further factor which must be considered is the protection given against single phasing by multiple-pole circuit-breakers, in that a fault on one phase trips all three phases. As a result, triple-pole circuit-breakers are being used very successfully for immediate back-up protection for 3-phase motors.

In my experience a maximum rupturing capacity of about 5–6kA seems to be all that is required in this country on the type of application normally considered suitable for miniature circuit-breakers. I would not dispute that higher prospective fault currents exist, but the resistance alone of a 20yd run of 7/·064 cable is sufficient to reduce "infinite" busbars to 5–6kA maximum prospective fault current. In addition, it is very rare that a fault reaches full maximum prospective fault current in this type of application.

I have gained the impression that the authors imply that making capacity is not really as important as breaking capacity, and that a making capacity of about half the breaking capacity may be considered satisfactory. I cannot agree with them on this point, as I consider the design of the circuit-breaker should be such that the making capacity is at least the equivalent of the breaking capacity. In service the immediate reaction to a circuit-breaker tripping under fault conditions is usually to attempt to reclose it, and if it has cleared on a fault within its breaking capacity but above its making capacity, this may have serious consequences.

It would appear from the Tables that there is a greater margin on the whole between the first cost of circuit-breakers and that of equivalent switch-fuses in this country than there is in the United States, which we would accept as a result of the greater production of miniature circuit-breakers in the latter. Against that we must off-set the flexibility of application and negligible maintenance costs.

Mr. M. P. Reece: I propose to comment mainly on that portion of the paper dealing with arc chutes. I agree that arc chutes are not altogether as simple as they might appear to be: their design is to a certain extent rather more of an art than a science, and slight changes in design greatly affect their performance. However, I consider that in certain cases the performances quoted by the authors could be improved upon.

I should like more details of the performance of miniature circuit-breakers designed for a.c./d.c. operation in d.c. circuits. How do they behave when interrupting currents intermediate between fault and load currents? For instance, a miniature circuit-breaker that will interrupt 700amp and 7amp with ease may interrupt 70amp only with great difficulty, since the blow-out forces decrease approximately as the square of the current in a series-excited circuit-breaker, and low currents are interrupted satisfactorily without blow-out.

The effect of carbon arcing tips has been raised in the paper. It is stated that an arc in a miniature circuit-breaker between carbon tips is hotter and more destructive than a similar arc between metal electrodes. I do not consider this to be necessarily true. The temperature of, say, a 1kA arc 2cm long in free air between carbon electrodes may be higher than that of a similar arc between copper electrodes, because of the lower ionization potential of copper. However, when an arc is forced into an arc chute and constricted, its temperature depends very largely on the amount of constriction and the cooling it receives, the temperature rising as it is constricted and cooled.

Carbon tips seem to give a more destructive arc because the carbon, having a high boiling-point and low thermal conductivity, rapidly gives copious thermionic emission, which leads to very low re-ignition voltages. Thus a longer arc or one with a higher re-ignition voltage gradient is required than with metal electrodes, whose much lower (for copper, negligible) thermionic emission gives a re-ignition voltage comparable in some cases with the circuit voltage. Thus with carbon tips the arc is longer, dissipates more energy and persists for a longer time, so increasing the damage to the circuit-breaker.

Mr. E. W. Semmens: It is a fact, of course, that the miniature circuit-breaker is used in great quantities in various countries, and it is hard to undertand how this country lags behind, since miniature circuit-breakers have been marketed for something like 25 years. The war cannot be blamed, since Germany is a very large user of the device.

Figs. 7 and 9 contain curves of instantaneous operation at 5–10 times full load, while curve (*c*) in Fig. 11 shows zero time at 220% full load. I may be misinterpreting this, but I should like a little more detail.

Curve (*b*) shows an operation time exceeding 60sec, whereas a miniature circuit-breaker of this type clears in approximately 30sec at 150% load. Was curve (*c*) obtained with 100 centistokes silicone fluid?

Section 7.2 contains most interesting information. I have no doubt that maintenance costs would outweigh initial costs, but even if this were not the case, the loss of production due to fuse finding and the time required for replacement can be very serious and very costly.

I should like the authors' views on compensation for ambient temperatures; it is very important, and I know that rapid strides have been made in other countries.

Other speakers have stated that there are other forms of miniature circuit-breakers, with instantaneous and inverse-time characteristics, manufactured in single-, double- and triple-pole types, which have many applications. It is also clear that miniature circuit-breakers can be provided with auxiliary contacts to perform all sorts of duties in connection with alarms, etc., which come into operation when the miniature circuit-breaker operates. Calibration is also provided now on circuit-breakers, which is a very useful asset. One can therefore adjust the tripping times to meet the particular load conditions, which may vary from time to time.

Finally, when it is realized that miniature circuit-breakers provide direct and immediate indication of the circuit that has been interrupted and that free-handle mechanisms prevent reclosing, I feel that there must be a big future for miniature circuit-breakers, and the number of discriminating users in Britain will, I am sure, greatly increase.

Mr. H. W. Baxter: Fig. 11 shows comparative curves for a miniature circuit-breaker and a fuse that might be misleading, since the authors have chosen a class-Q fuse, which is not the best for close over-current protection: the class-P fuse is more appropriate for this purpose, since the fusing factor must not exceed 1·25. Such fuses are readily obtainable, will carry their rated currents indefinitely, and can be provided with a reliable indicating device. They can also be supplied with sufficient time-lag to cope with the overshooting of tungsten-filament lamps mentioned by the authors. I have used commercial fuses with a fusing factor as low as 1·15, and I do not think a lower value is normally required, since critical protection of circuits is not usually considered necessary.

If the scales in Fig. 11 had been appropriately chosen they would show that, with a large over-current, the fuse operates much more rapidly than the miniature circuit-breaker. The authors are aware of this, since they advocate the use of a fuse

to protect the circuit-breaker when it is unable to cope with the fault current.

An important feature of a fuse is its ability under large-fault-current conditions to interrupt a circuit before the current reaches a dangerous value. Since a miniature circuit-breaker has a more-or-less fixed minimum operating time, which, the authors state, is about 10 millisec, there is no cut-off effect and the current will reach a value that is limited only by the impedance of the circuit.

How does the arc energy vary with the prospective current? Since the magnetic blow-out increases the arcing voltage, I should expect the arc energy to increase with the current. The amount of energy that a device can withstand usually bears some relation to its physical dimensions, and so one would expect a miniature circuit-breaker to have a relatively small breaking capacity.

Section 7 seems to need amplifying, since the replacement of a blown fuse does not take 50 min. What proportion of this time was spent in finding the electrician, in his getting to the fuse board and in tracing the faulty circuit?

Mr. R. A. Marryat: Have the authors considered any way of backing up the miniature circuit-breaker other than by the use of h.r.c. fuses?

We know that miniature circuit-breakers have certain advantages, inasmuch as they can be fitted to provide core-balance earth-leakage protection, which may be of considerable importance in domestic installations and many other installations in commercial buildings. Would there be any serious drawback if an ordinary choke were fitted in series with the installation, so as to reduce the prospective short-circuit current to a figure which the miniature circuit-breaker could accommodate? At least in small houses I do not think that would be a serious disadvantage.

If the circuit-breakers could be made to a guaranteed short-circuit rating of, say, 5 kA and the choke limited the maximum current to 5 kA, we could ensure safety. I imagine that the voltage drop would not be serious.

Mr. A. Hawes: It is regrettable that extremely little has so far been said about the d.c. applications of the miniature circuit-breaker. In road and rail traction and marine applications, and in a number of industrial processes, direct current is often the most suitable form of power supply, where reliable protection, with quick indication, of the control and auxiliary circuits is of prime importance. This is particularly so in rail traction, where train delays of 30 min or more have been ascribed to a control-circuit failure simply because a blown fuse could not be located rapidly. It is our experience that the so-called indicating fuses rarely indicate.

As an example of the economies that could be obtained by the use of miniature circuit-breakers, the railway system with which I am associated has an annual consumption of 20 000 traction-type (both 600 and 70 volt) cartridge fuses a year. We estimate that if a 600-volt circuit-breaker can protect the circuit twelve times without failure, it will repay its initial cost, compared with the switch-and-fuse arrangement normally fitted. The corresponding figure for 70-volt circuits is as low as four times. We have had a trial installation of miniature circuit-breakers in service for some time now and have sufficient confidence to enable us to equip ten trains with all the 70-volt control and auxiliary circuits protected by miniature circuit-breakers. Back-up protection is provided by h.r.c. fuses in the main motor-generator and battery circuit.

Experiments are at present being carried out with 600-volt circuit-breakers, but much careful design work is required, especially in connection with blow-out and arc-quenching arrangements that will operate satisfactorily at low switching currents as well as on heavy faults. Considerable difficulty is being experienced in obtaining a reliable time-delay feature with d.c. circuit-breakers.

There is a very wide, although specialized, field for the application of d.c. miniature circuit-breakers which it is hoped the manufacturers will not neglect.

Mr. G. O. Watson (*communicated*): The authors refer to the extensive adoption of the miniature circuit-breaker in the United States, but it is worthy of note that they are already firmly established in Germany and Italy. For instance Italian shipowners are very firm in their preference for them instead of fuses in distribution circuits, and many examples could be quoted; noteworthy is the S.S. *Cristoforo Colombo* recently completed. This ship has the second largest a.c. installation in the world, having a total generating capacity of 8 MVA at 440 volts. Circuit-breakers are used to the exclusion of fuses throughout, including 2 900 miniature circuit-breakers. In another Italian vessel, the S.S. *Andrea Doria*, having a d.c. system, 2 500 miniature circuit-breakers were installed.

It is always undesirable to issue standards until some service experience has been gained, but undue delay in publishing may embarrass manufacturers who are already in production. The authors' plea for a British Standard therefore deserves support. In addition to the Australian Specification referred to, it is understood there are two South African Standards, one for miniature circuit-breakers for the protection of electric motors and the other for lighting, heating and domestic installations. In Germany there is V.D.E. Specification 0641/1.52.

The selection of back-up protection requires very careful consideration, since to be of any value the back-up device must break the circuit before the current reaches a value greater than that which would disrupt the circuit-breaker. Generally speaking, ordinary switchboard circuit-breakers having greater inertia of moving parts would be unsuitable, and it would appear that fuses are more appropriate. Lloyd's Register of Shipping requires that, where the declared breaking capacity of the circuit-breaker is less than the prospective short-circuit current with which it may be called upon to deal, it must be backed up by a fuse of suitable category of duty (or by a circuit-breaker with instantaneous trip) which will operate at not more than 90% of the short-circuit rating of the circuit-breaker.

It is unfortunate that miniature circuit-breakers have been used for purposes for which they were never intended, and it is important that users should appreciate their limitations. Cases have occurred in ships where they have been placed on main switchboards without back-up protection, and they have not stood up to the job. Furthermore, if the circuit-breaker is to be used as a switch, i.e. opened and closed frequently, the life of the mechanism and contacts becomes important. When they are installed on main switchboards there is also the consideration that the busbars are practically never dead, and cleaning and maintenance of contacts and latches or even the removal of a complete circuit-breaker for replacement must be done on a live busbar.

While this type of circuit-breaker can be designed to deal with comparatively large short-circuit currents, closing on a short-circuit or heavy overload is more limited, and from this point of view single-pole switches would give better service than multi-pole units. The first to be closed would be available to clear the circuit.

The authors mention copper–tungsten or silver–tungsten as having proved excellent for contact material. In this connection one maker carried out extensive research with several alternatives and ultimately found that an alloy consisting of 93% copper, 5% silver and 2% cadmium gave the best results.

[The authors' reply to the above discussion will be found on page 379.]

NORTH-WESTERN UTILIZATION GROUP AT MANCHESTER, 10TH JANUARY, 1955

Mr. E. Roscoe: When miniature circuit-breakers are submitted to a competent testing authority there is little difficulty in determining the characteristics and technical performance to ensure that they have been correctly designed and are manufactured to specification. One equally important problem to the supply engineer, however, is that they are well and consistently manufactured so as to give long years of service without failure due to poor manufacture.

An opportunity arose recently to test 20 circuit-breakers which had been in service for some 25 years in a large house where there was a large connected load. The circuit-breakers were used on sub-circuits, and an inspection indicated that many of them had operated, some of them under rather heavy fault conditions. They were marked for 15 amp and 250 volts, but it was not indicated whether 15 amp was the normal current-carrying capacity or the tripping current. Each circuit-breaker was tested in turn, and the minimum tripping current for any was in the region of 25 amp, while the maximum current on a few of them was 120 amp; three failed to operate. On inspection it was found that the wax which was poured into the base of the cover to seal the screws which support the mechanism and go through the base, had melted and flowed on to the base of the cover, so making contact with the armature which trips the breaker on overload. Thus, three out of the 20 were inoperative due to a minor defect in construction. The wax was tested for melting point, which, in accordance with clause 29 of B.S. 862, should be 100° C: the wax actually melted at 80° C. A further close inspection revealed that one of the stems was loose in the base, owing to bad riveting, and this caused local heating and consequent flowing of the wax. The wax in a new circuit-breaker was then tested and found to melt at 80° C.

However much care is taken in the technical design of circuit-breakers, if such defects in their manufacture are allowed to pass, failure to operate is inevitable, with possible serious consequences in service.

Mr. G. W. V. Buckle: The figure of 15 000 operations as a specified life given in Section 3.2.1 appears desirable. This figure, however, for the number of operations in endurance tests varies between different specifications, examples of which follow:

(*a*) The draft New Zealand code of practice for miniature circuit-breakers for use on a.c. circuits calls for a similar number of operations to that in B.S. 862, Section 36, namely 500.

(*b*) The Italian National Committee of the C.E.E. Standards for small automatic over-current switches for nominal currents up to 25 amp calls for 4 000 operations at nominal current and highest voltage at power factors between 0·6 and 0·7 with fixed speeds of operation.

(*c*) The Canadian Specification CE.S.A.C.22.2 No. 5, 1942, for circuit-breakers in the range under discussion calls for a total of 10 000 operations, of which 6 000 shall be at nominal rated current and voltage.

(*d*) The American Standards Test Code for low-voltage circuit-breakers bases this on the interrupting rating or capacity, i.e. 50 000 operations up to 15 kA at no load, with 2 500 before any servicing shall be done.

The last paragraph of Section 5.1 gives an extract from the Australian specification, but I would point out that somewhat similar clauses are included in the New Zealand and the Canadian specifications referred to previously.

The Canadian specification for circuit-breakers rated at a nominal current of less than 100 amp and less than 250 volts requires an actual current breaking and making capacity of 5 kA at least three times for single-pole circuit-breakers. The New Zealand specification requires rating and breaking through three tests on prospective maximum short-circuit values rising to 1·5 kA in the light-duty category and 3 kA in the heavy-duty category. The C.E.E. specification gives a series of making and breaking tests from 1 amp up to 500 amp at power factors between 0·3 and 0·4 for currents up to 60 amp and at unity power-factor for heavier currents. Personally I feel that a prospective maximum short-circuit current of 5 kA is desirable. The method of testing and rating should be in accordance with A.S.T.A. publication, which would secure uniformity of test pending the introduction of a clause 40 to B.S. 862. I agree that the time has come for a British Standard covering miniature circuit-breakers. For lower ratings, owing to their own impedance, the circuit-breakers become self-protecting, and I believe the word "prospective" in this paragraph should read "actual."

No indication is given of the ratio of the reduced values of making capacity, but I believe the authors will agree that this figure is probably of the order of 40–50%.

Mr. H. P. D. Rendell: In the rewireable fuse the element itself is subject only to ageing and annealing of the metal of which it is composed; the characteristics of the element can be determined by experiment or analysis. The miniature circuit-breaker, on the other hand, incorporates a mechanism including springs and contacts, as well as such electro-mechanical features as a bimetal strip and solenoid. How does the fatiguing of the mechanical parts compare with the fuse? Is the thermal-trip mechanism subject to warping after a number of operations?

Is the miniature circuit-breaker comparable in size with, say, a rewireable fuse of the same capacity?

A serious fault can be cleared by a rewireable fuse of the right design and the element replaced at low cost. If the fault is such that the miniature circuit-breaker is incapable of clearing it without serious damage to itself, thus necessitating a complete replacement, how does the cost of such replacement compare with that of a length of fuse wire?

Mr. W. G. Hewlett: The paper does not make reference to the comparative efficiency of miniature circuit-breakers on d.c. and a.c. supplies, or on 3-phase compared with single-phase circuits. Will the authors comment on this point?

Mr. C. Ayers: I have always understood the term "circuit-breaker" to refer to a mechanism which has a definite rupturing capacity. Granted that the miniature circuit-breaker has some rupturing capacity—an estimate of the useful breaking capacity being some 0·25 MVA—it appears to be something of a cross between a circuit-breaker and a contactor, the latter being limited in rupturing capacity to some eight times its rating.

The circuit-breaker is used to handle high prospective short-circuit currents and to provide discriminating protection in a network. The fuse can handle high prospective short-circuit currents, but does not afford the degree of discrimination given by the circuit-breaker. It also has the unique characteristic of cut-off not possessed by a circuit-breaker. The contactor, normally backed up by a fuse, is used on circuits requiring frequent operation and in its smaller sizes affords an economic and technical solution; its field of application has limitations, however. This new mechanism appears to have a definite field of application on circuits whose prospective current does not exceed 1 kA and where close discrimination is not essential.

It appears from Fig. 7 that the tripping characteristic of the mechanism is inverse, with a minimum operation time of 1 min at six times rating. Thereafter as current increases and after an indeterminate zone, it operates in some 10 millisec. If this is the case, then cables, even if correlated to the circuit-breaker rating, and motors, will be very close to their thermal rating on a fault current of six times full load. The advantages of fuse protection in this case is shown by Fig. 11, where the fuse characteristic (*a*) operates more rapidly than the circuit-breaker

curve (*b*). Does curve (*a*) represent the pre-arcing time/current characteristic of a fuse with a fusing factor of 1·75?

In Section 6.3 the authors appear to hold the view that the fuse is of no use in motor protection; I should like them to explain their views in more detail, as I have always understood that if contactor starters are employed, a back-up fuse is essential. It is worth bearing in mind in this connection that if 80% voltage on the terminals of a 10 h.p. motor with direct-to-line starting is desired, the supply should have a prospective fault capacity of not less than 0·25 MVA—the limit of a miniature circuit-breaker.

The scheme described in Section 6.4 and illustrated in Fig. 12 is interesting and points out one application of the device. However, since at currents above six times rating all circuit-breakers trip in the same time, how is discrimination obtained?

The economic comparisons given in Section 7 are worthy of note. Since the items compared have different short-circuit capabilities, has cognisance been taken of this fact in the full installation comparison?

The device as described by the authors is of interest in that an attempt has been made to obtain a rupturing capacity, however low, and if developed and modified for remote control, etc., could possibly have a far-reaching significance in the market now met by contactor gear.

Mr. H. Lever (*communicated*): The authors rightly point out that, while it is standard practice to examine a large circuit-breaker after a severe fault, this would hardly be expected in the case of miniature circuit-breakers. Therefore, if the reclosure of a miniature circuit-breaker after a fault restored the supply to the circuit it protected, no further action would be taken and it would be assumed that the miniature circuit-breaker was undamaged. If, however, it had been damaged, it might fail to clear a further fault, which could have more serious consequences than the blowing of a fuse due to deterioration. A fuse, whether it be rewireable or h.r.c., always fails to safety; the same cannot be said of a miniature circuit-breaker.

More details could have been added with advantage to Fig. 12. For instance, are the rectangles immediately below the pilot lights meant to indicate miniature circuit-breakers? If so, I cannot see the necessity for them.

The authors advocate the use of miniature circuit-breakers in domestic installations, and while I agree that they have distinct advantages over fuses, their much higher cost will deter architects, contractors and house-owners from installing them at present. In my experience, very little trouble can be attributed to fuses in properly designed house wiring, and the little inconvenience involved does not warrant spending a sum which might add as much as 25% to the total installation cost when dealing with 6- or 8-way service units, ring mains, cooker fuses, etc.

In the installations with which I am concerned, there are nearly 600 h.r.c. fuses in the range 2–250 amp capacity. These are installed over a very large area—some being in remote places as far as 50 miles from the nearest electricians' depot. During three years a total of 180 fuses were replaced at a cost (excluding labour charges) of £11. Most of the fuses are of a type which can be reclaimed either by fitting new elements on site or by returning the cases to the manufacturer for rewiring, and the latter alternative has been adopted. The cost of new replacements would have been £31. Very little time was spent by electricians in replacing fuses—the majority being replaced by plant attendants whose normal duties were not interfered with. Many of the fuses protect circuits in important water-pumping plant, but no interference with pumping has been caused by blown fuses. Miniature circuit-breakers would have cost approximately £300 more in the initial installations. Allowing £4 for skilled labour (a generous allowance) in addition to the £11 for fuses, the average annual cost was only £5. Fuses were obviously more economical than miniature circuit-breakers in this instance. Miniature circuit-breakers will no doubt have applications, especially in industrial installations, but each installation must be considered in some detail before a decision can be reached.

The above example is only an overall comparison and includes a large proportion of 15 amp 3-phase distribution boards which are almost double the cost when fitted with miniature circuit-breakers in place of h.r.c. fuses. (Incidentally, Table 5 would be more representative if an example of 15 amp 3-phase distribution boards had been included.) In the 30 amp 3-phase sizes there is very little difference in price. Could the authors say whether future developments are likely to have a levelling effect on the prices of 15 amp sizes, as I believe that miniature circuit-breakers will not gain ascendancy over fuses until this is brought about.

[The authors' reply to the above discussion will be found on the next page.]

NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 24TH JANUARY, 1955

Mr. C. G. Whibley: The authors draw attention to the British traditional outlook and what they term the bias towards fuses. It is worth while to examine the reasons for this bias and the effect upon application policy that will result by using miniature circuit-breakers.

This so-called bias towards fuses has resulted in the development in England of very compact fuse-assemblies in the 15–60 amp range suitable for prospective fault currents ranging from 16 kA for 15 amp 250-volt fuses up to 46 kA for 60 amp 440-volt fuses. In the United States, circuit-breaker development was given preference, and this was particularly assisted in the lower-current range by the fact that 120 volts was the more usual phase-to-neutral service voltage.

As pointed out by the authors, the prospective fault currents which can be handled by miniature circuit-breakers of the 15–60 amp ratings are limited to approximately 3–5 kA. Calculations have shown that the prospective fault currents at service points in certain domestic installations, e.g. flats, will be as high as 10 kA. There is a wide field where the prospective fault currents may be much lower than this.

It is therefore clear that if small circuit-breakers are to be widely used in place of fuses, it will be necessary to educate the user to the fact that he must know the prospective fault-current at the point of application, whereas in the past he has been able to install cartridge fuses of a known maximum rating anywhere in a particular section of his installation without the need for special calculations.

Mr. T. H. Sutcliffe: Have the authors any information regarding the operation of circuit-breakers carrying current for a long number of years without having operated? This state of affairs would undoubtedly obtain if miniature circuit-breakers replaced present-day fuse-boards in domestic premises.

On the distribution schematic on the heating-circuit side there are shown thirty-nine 15 amp ways outgoing. Can one assume that the devices marked T are 200 amp circuit-breakers?

A criticism of miniature circuit-breakers in the past has been of the types which rely on gravity for dropping the handles or indicators and failing to do so although they have cleared the fault. This is particularly annoying in such cases as theatre switchboards, with perhaps 50 or more circuit-breakers involved.

Mr. D. Rudd: I am interested in the possibility of using these

circuit-breakers to replace lighting distribution fuse-boards in generating stations. A major obstacle appears to be that the fault level may be as much as 5 MVA on a 240-volt single-phase board and probably averages 2–3 MVA. This is considerably greater than the 1 MVA rupturing capacity of existing designs mentioned in Section 5.2 of the paper. Can the authors see any prospect of higher rupturing capacities in future designs?

Mr. D. Riach: In Section 4.2.1 it is stated that a considerable drawback of thermal trips is their long resetting time. This feature, however, is advantageous for motor protection, for it ensures that time is given for the motor to cool, thus preventing a burn out.

Mr. A. T. Crawford also contributed to the discussion at Newcastle upon Tyne.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. H. W. Wolff and **T. G. F. Atherton** (*in reply*): We should first like to reply to those speakers who have referred to the various duties and types of miniature circuit-breakers not dealt with in the paper. We purposely concentrated attention on the most important aspects in this sphere, and the one likely to find the most widespread application, i.e. protection against overload and short-circuit in sub-circuit distribution—since the space available prevented us from dealing adequately with all types.

We agree with those speakers, and in particular with Messrs. Flax, Robbins and Semmens, that triple-pole circuit-breakers are a necessary complement to the single-pole type and are essential in the protection of 3-phase motors against single-phasing. Earth-leakage circuit-breakers are also of steadily increasing importance, particularly in agricultural areas, and the development of the core-balance type has lent further emphasis to this application.

For the same reason we have, except for a few remarks, excluded d.c. design and performance from the scope of the paper. As pointed out by Messrs. Reece and Hawes, this is a very important branch of application for miniature circuit-breakers, but it is also a specialized one requiring its own treatment. Generally speaking, the majority of British designs are basically "a.c. designs" with slow-make and slow-break manual contact operation, capable, however, of operation on a d.c. supply, usually at a reduced voltage, and with a substantially lower breaking capacity. Unless special care is taken in the design of contacts and mechanisms, difficulties may be experienced in breaking low or medium direct currents. It is unfortunate that those desirous of using miniature circuit-breakers for d.c. applications have little to choose from, and usually have to carry out tests to ascertain suitability for individual applications. This applies, in particular, to electric traction.

We feel that the technical matters can be dealt with most satisfactorily under three headings:

(i) Non-deterioration and "life."
(ii) Time-delay characteristic.
(iii) Short-circuit performance.

(i) Mr. Roscoe has raised a very important point. Obviously it is essential that at least reasonable consistency be achieved in manufacture, or the best design will be ruined. This means 100% interchangeability of parts and rigid inspection, and is all the more important since we expect a very much closer accuracy from a circuit-breaker than from a fuse. The gradual simplification of switching and tripping mechanisms has contributed considerably towards making possible consistent bulk production. Mr. Buckle has usefully drawn attention to the various views that exist on the subject of the "life" expected from a miniature circuit-breaker. We feel that the value of 15 000 operations is a maximum that will meet all usual requirements and that, in fact, even half that value might prove quite satisfactory.

The questions on non-deterioration put by Messrs. Rendell and Sutcliffe are perhaps the most difficult ones to answer, chiefly because so far there has been little experience in this country on the widespread application of miniature circuit-breakers. Simplicity of design, avoidance of ferrous metals, rust proofing of those ferrous parts which must be used, silver-plated or solid silver contacts, the use of as few rotating parts as possible—all contribute towards assuring continued efficiency. The best proof may be found, perhaps in referring to those countries like the United States where miniature circuit-breakers have given highly satisfactory service for over 25 years.

(ii) In answer to Mr. Semmens we would point out that Fig. 11 has a logarithmic ordinate, so that in actual fact it does not indicate the value where instantaneous tripping commences, as do Figs. 7 and 9. We also confirm that curve (*c*) of Fig. 11 was obtained with 100 centistokes silicone fluid. Silicone fluid was used because of its low viscosity temperature coefficient. Considerable strides in ambient-temperature compensation have been made. In addition to the means already mentioned in Section 4.2.1, swamping of the ambient-temperature effect may be mentioned.

Mr. Ayers raises the question of the value of the instantaneous trip ratio. It is certainly not limited to 6 in all cases, but varies from one design to another between values as different as 4 and 12. In some designs it can be set within quite wide limits during calibration in order to cater for special applications and, in particular, to provide means of discrimination. Curve (*a*) of Fig. 11 is the characteristic for an h.r.c. fuse with a fusing factor of 1·55. We appreciate the reference to class-P fuses made by Mr. Baxter, but hold the view that their use has been reserved to special cases. The great bulk of fuses installed are class Q, with an average fuse factor of 1·6, as compared with the normal tripping factor of 1·25 for circuit-breakers.

(iii) Section 5 opens by stating that "Of all the points concerning miniature circuit-breakers, rupturing capacity is perhaps the most controversial and the one of the greatest technical interest to engineers and users." This has certainly been borne out at all the discussions which have so far been held.

It is not contended that miniature circuit-breakers compete with h.r.c. fuses in rupturing capacity, nor is it denied that large fault currents do exist, but only exceptionally. Broadly speaking, miniature circuit-breakers have the same short-circuit capacity as equivalent semi-enclosed fuses, and if high prospective fault currents were as common as some speakers have made them out to be, failures of semi-enclosed fuses would be frequent, to say the least. In actual fact, failures of these fuses are extremely rare, and we therefore emphatically deny the need for ascertaining the prospective short-circuit current each time before installing miniature circuit-breakers. Locations with high fault levels are usually sufficiently well known.

If there are any doubts as to the short-circuit capacity of the supply, back-up protection must, of course, be provided, usually by means of h.r.c. fuses. This does not mean that every circuit-breaker ought to have one such fuse behind it. Group back-up protection as recommended by Lloyd's Register of Shipping can usually be achieved satisfactorily, if the fuse rating is correctly chosen.

Dr. Einhorn rightly points out that back-up protection by h.r.c. fuses may entail difficulties as regards discrimination. If the fuse rating is chosen to be too low, the cross-over point will

occur too soon so that the fuse may blow unnecessarily in a region where the miniature circuit-breaker would function quite satisfactorily. On the other hand, if the fuse rating is too high the back-up protection may not operate as efficiently as it should at currents just in excess of the capacity of the circuit-breaker. In many cases it has been found that a 100 amp h.r.c. fuse gives a suitable cross-over point at about 2 500 amp.

We are indebted to Mr. Reece for the additional information concerning carbon-arc tips and their behaviour on breaking heavy currents. We agree with Mr. Buckle that the making capacity is usually considerably lower than the breaking capacity. We do not intend to imply thereby that it is any the less important. We further endorse Mr. Baxter's view that to a considerable extent the rupturing capacity is a function of the physical size.

In reply to Mr. Marryat there appears to be little need for the installation of chokes in domestic premises, since prospective fault currents are nearly always well within the capacity of the circuit-breaker. Where high fault currents may occur, h.r.c.-fuse back-up protection is normally adopted, and we are not aware of chokes having been used in this connection in order to limit fault currents.

In reply to Messrs. Swann and Hewlett, the performance of triple-pole types as compared with their single-pole counterparts depends largely on the design. If care is taken properly to separate and insulate the three phases a better performance can in fact be achieved than with single-pole types, but if the phase separation leaves something to be desired, a considerable reduction in breaking capacity may be expected.

With regard to the application and economy of miniature circuit-breakers, as mentioned by Messrs. Swann and Robbins, substantial savings in cable sizes are possible by using miniature circuit-breakers instead of fuses, particularly with the small cable sizes where the choice depends on the current-carrying capacity rather than on the thermal rating.

Mr. Hawes has provided some interesting data concerning fuse expenditure on electric traction, and is unlikely to have left any doubt as to the importance of miniature circuit-breakers in this field. Mr. Watson has most usefully completed this information with details of circuit-breakers installed on Italian ships. He has also drawn attention to the importance of plug-in circuit-breakers for applications where withdrawal from the busbar for isolation or replacement is desirable without necessitating the interruption of the supply.

In reply to Mr. Rendell it will be found that there is little difference in size between a miniature circuit-breaker and a semi-enclosed fuse of equivalent maximum rating and capacity, the fuse being if anything a little smaller.

We agree with Mr. Lever that in many cases individual installations should be considered on their merits. We feel that the use of a 50 amp circuit-breaker as against a 15 amp fuse has had considerable influence on his comparison. Present and future developments are likely to improve considerably the case for miniature circuit-breakers.

In reply to Mr. Sutcliffe, circumstances relative to the diversity factor for the installation illustrated in Fig. 12 required only a 60 amp rating for the circuit-breakers T.

Several speakers have drawn attention to the possible misuse of miniature circuit-breakers, and we should like to emphasize again that like all other protective equipment they have their limits, and in some cases prejudice has come about through using them on duties for which they are not intended.

We agree with Mr. Swann that widespread application of miniature circuit-breakers is bound to lead, in due course, to a revision of several clauses of The Institution's Wiring Regulations, and we share the views of Messrs. Watson and Buckle that the time has come for a British Standard to be prepared on miniature circuit-breakers. In fact, such a Standard is already in the course of preparation.

DISCUSSION ON

"THE LOGICAL APPROACH TO THE PROBLEMS OF SPACE WARMING BY ELECTRICITY"*

EAST MIDLAND CENTRE, AT NOTTINGHAM, 18TH MARCH, 1952

Mr. E. G. Phillips: I am in agreement with the basis of the paper, namely that better thermal efficiency can always be obtained by adequate insulation. Therefore, why restrict its use to electrical heat only, and forget all the other fuels? The insulation is a source of efficiency—not the fuel.

For eight years I have been concerned with the national aspect. My interest is not in power-station loads, or in anything to do with the electrical industry. Economy in the use of coal is the basis of my approach.

The elimination of visible smoke and corrosive gases is very desirable, but discharging the products of combustion 350 ft above ground level does not mean that these grits and gases are eliminated.

The efficiency of modern power stations was stated by Mr. Roxbee Cox, Chief Scientist to the Ministry of Fuel and Power, to be less than 20%. This figure is slightly lower than the one given by the author, but it matters little since we cannot at present build these specially insulated houses, which is the first essential before we consider fuel efficiency.

District heating is stated to be very expensive and not exactly desirable. Much of my business life has been spent in hospitals and similar institutions. For large blocks of buildings spread over vast areas district heating is the only practical form of comfort heating. There is plenty of evidence as to its usefulness and efficiency, and it is still being installed as the most efficient and best way of heating buildings of this character.

With regard to closed or semi-closed solid-fuel stoves, it is stated that they need anthracite or a high-grade fuel. If they did not heat a room satisfactorily on the fuels available they would not be selling at the present rate. The demand is such that it now exceeds the rate of production, and there is much evidence that they offer a definite economy in fuel.

The author states that space heating means giving heat to the body. I would rather consider the approach not as a question of *space* heating but *comfort* heating. If the temperature of the air in the room is a few degrees higher than my body temperature, I am warm—so long as I am not subjected to draughts. Radiant heating is the most satisfactory form of heating. The days of the cast-iron radiator and convector heating are both long past, and every effort should be directed to the question of understanding radiant heating—but whether high- or low-temperature radiation, we cannot discuss here.

The author states that the present-day houses are "designed to burn four tons of fuel a year." Why design the houses as we do? Why not design them *not* to burn 4 tons per annum? A house designed to a U value of $0 \cdot 07T$, which is the overall efficiency that the author requires, could not be built for £1 500, if we take into account the insulated walls, the air-tight window frames and all other requirements. A more likely figure would be £2 500.

I think that heat pumps are at present too expensive for practical purposes, but a source of heat worthy of consideration is the sewers. It is suggested that the heat pump could be a means of taking the low-grade heat out of the sewers and putting it back where it came from, i.e. into the house.

The use of double glazing should be compulsory since it reduces fuel consumption. The author suggests evacuating the space between the sheets of glass, but this is not really practical on large sheets or panes of glass.

The author mentions cable in concrete in the floor. What type of cable would he use and how would he lay it? Furthermore, how would he get it out again if a fault developed? What is the life of a cable buried in concrete?

The author proposes to heat the whole of his house for $1 \cdot 5$ kW, which is equivalent to 5 000 B.Th.U., i.e. for a little less than $\frac{1}{2}$ lb of coal per hour. Even at a U value of $0 \cdot 75$ this would be difficult.

The suggestion that floor heating gives a long heat time lag, so that with load shedding the temperature of the house would not fall, prompts the rejoinder that the reverse is also the case. When it is cold it will take several hours before the temperature can be built up again.

The question of remission of taxation has been ventilated and discussed at every meeting of the Fuel Efficiency Committee of the Ministry of Fuel and Power for many years, but it is a great problem to try to persuade the Treasury to recompense those persons spending capital to effect a reduction in the consumption of fuel, and success seems dubious. From practical experience, I do not believe that the heat exchanger would give the very excellent results that are anticipated. With this exchanger in the roof space, can cleanliness of the three hundred $\frac{1}{4}$ in tubes be ensured? Can the fan be guaranteed to be noiseless, and what happens on a foggy day?

Mr. H. L. Jones: Comfort conditions for the human being, who has a body temperature of 98° F, are determined by the control of that temperature. In still air of about 58° F the body loses heat continuously and the person is comfortable. It is essential that the heat given up from the body should be absorbed, and it is by controlling the cold that comfort conditions are obtained.

Heat can be lost from the body by conduction to the air around it, by convection and by radiation. There are several ways of controlling the loss. One can put clothing around the body to help keep the heat in. If we build a house around the body we can control the air temperature and thus the loss of heat by conduction. We can control the loss of heat by radiation by surrounding the body with radiant heat, as when we sit in the sun. The loss of heat can be controlled very readily by raising the air temperature above the normal room temperature.

During the war some prefabricated buildings were impossible to heat-insulate owing to the shortage of materials. They were probably composed of 75% glass and 25% concrete. It was difficult to raise the air temperature in these buildings to 60–65° F by convectors, but if radiant heat (or infra-red heating) was used throughout, the building was quite comfortable to work in with an air temperature of only about 40° F. I therefore suggest that we should aim primarily at the use of radiators for space warming, since they produce a comfortable condition on the human body.

* PARRY, D. H.: Paper No. 1220 U, December, 1951 (see 99, Part I, p. 233).

However, for maximum efficiency we must first insulate the building. Alternatively we can prevent radiation from the walls by some method, such as a covering of aluminium or tin foil, and so cut down the heat loss from the body. In order to achieve comfort we must either fully insulate to prevent loss of heat by radiation or increase the supply of radiant heat.

Dr. J. H. Mitchell: It is certain that the demand for the by-products of coal distillation will continue to increase to such an extent that we shall find it impossible to supply sufficient coal for all our needs. It seems, therefore, that we shall have to use the gas and coke resulting from distillation for heating purposes—the gas directly and the coke, if possible, for power-station boilers. Of course, new developments in atomic-energy research might lead to a radical change in this position. When I consider the methods of generating electricity at present used in power stations it seems that there is a considerable heat wastage in the water from the turbines, which might be used. For example, the wasted heat from Wilford power station could perhaps be used to heat the neighbouring suburb of West Bridgford instead of being used, as at present, to heat the river.

Mr. A. B. Moore: I notice that, without a heat exchanger, a temperature rise of about 15° F is obtained. With the heat from the exchanger that figure is increased to 23° F, assuming 60% efficiency, which I do not think can be maintained over a period of time. On a cold night with a frost of 10° F the temperature in a house will drop to 45° F in the morning, and so it appears that we must have background heat. The obvious answer would be to install more central-heating plant with a full heating capacity and to conserve the temperature of the floor, air space and the windows to eliminate heat loss. The best idea would be to install sufficient radiation surfaces to maintain comfortable conditions throughout the 24 hours. This could be done for less than the figures quoted in the paper. A cost of 4s. 1d. solely for central-heating load seems high, but I assume that an all-electric house is being considered. If the hot-water supply cannot be maintained for less than 10s. a week a very inefficient system is being used.

The author only includes one thermostat and relay, the total cost of which, including the cable, is £15. Would he install the thermostat in the centre of the room or near the outside wall? Would it be in the living room or the kitchen? When it cuts out, is the remainder of the house not heated?

If the heat exchanger broke down, what would happen in a house with all the windows closed?

Mr. W. R. Coleman: I wonder whether the author purposely avoided the question of commercial heating so as to consider on some other occasion the possibility of high-volume thermal storage overnight. This was used in some large buildings before the war, and could possibly be used for factories with a fan type of unit heater for space heating.

Mr. G. G. Clarke: A paper by Grierson* which was published during the war dealt with the warming and ventilation of air-raid shelters. Facts and figures were given which go a long way to prove that the warming of floors is superior to other forms of heating. By running heating ducts, the ground floor of a modern house can be warmed, or heating cable can be run in which will prove very effective. Grierson quotes Dr. Bedford, who suggested a best mean temperature of 60° F and asserted that, so long as that temperature is maintained in the room, the temperature of the floor can be raised above that of the air and still achieve the ideal temperature. By this means you can get a low air temperature or a high air temperature and maintain a low-radiation wall temperature.

With regard to the ventilation of the building described by the author, is there not a law which states that you cannot completely block up a room, but that there must be some form of ventilation?

The topping-up of solid fuel by electricity would be a tedious process, particularly as you would have to light a fire. There is, of course, the question of the warming-up time when floor warming is used. However, in Grierson's experience, when they had a cut-off of three hours from 7 to 10 p.m., it did not seem to affect the conditions appreciably, and I suggest that when a cut-off is of short duration, e.g. overnight, satisfactory limiting conditions of temperature for summer and winter would be achieved.

Mr. R. I. Morgan: Some of the previous speakers, who have advocated the use of radiant heating, appear to have missed the main point of the paper, since those houses using radiant heating must of necessity have a considerably higher maximum demand than fully insulated houses with heated walls and floors. One of the main objects of the paper was to further methods of heating which would reduce the maximum demand as now experienced.

In Section 9, does the consumption of 5 000 kWh at $\frac{3}{4}$d. per kilowatt-hour include that of the fan which the author advises, and has he made any allowance for houses with windows open?

[The author's reply to the above discussion will be found on page 390.]

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 14TH OCTOBER, 1952

Mr. W. G. Chilvers: The author's method of space heating calls for home life to be run on a more or less set pattern. Individual requirements for ventilation differ to a very great extent. One of the main advantages claimed for radiant heating is that the running cost can be predicted with some degree of accuracy because the number of air changes do not have any major effect. As the author has indicated, heating requirements are very largely linked with the capacity to pay. Experience at the Building Research Station brings out this fact very clearly, and experience with district heating schemes indicates first that, where whole-house heating is undertaken and where the cost is on a more or less fixed basis, the actual heat requirements increase considerably because there is no incentive to economize, and secondly, that one of the main objections of the users is that they cannot adjust their heating requirements to suit their pockets. This is not just a case of designing a heating scheme to fit an income group. The need is for flexibility from week to week. It seems quite certain that the average wage earner in this country regards space heating as almost a semi-luxury.

The most efficient way of using our coal resources for heating houses would seem to be to have one continuous-burning solid-fuel appliance, in order to provide space heating in the room most used and also water heating, and for the remainder of the house to be heated by electricity. It can be shown quite clearly that, for periods of up to six hours, less coal is consumed by using an electric fire than would be required to light a coal fire. Furthermore the standard of comfort required is reached much more quickly with the electric heater. This period of six hours covers almost all the normal requirements for rooms other than the living room, and the scheme has the very important advantage that the living room is warm in the morning and electricity is not required at breakfast time. The electric heater would be mainly used in the evening when some other room was in use. I think the electricity industry would be very wise to pursue this line of development at the present, and proceed with an examination of the possibilities for continuous space heating by electricity.

* GRIERSON, R.: "Space Heating by means of Electrically Warmed Floors as applied to Surface-Type Air-Raid Shelters," *Journal I.E.E.*, 1942, 89, Part II, p. 4.

The author's case rests very largely on the decrease in the thermal-transmittance value for buildings, and I very much doubt whether this can be reduced to 0·075 at the cost of £250 which he has quoted. I would appreciate his further observations on this in the light of information which he may have received since the paper was written.

We need practical information on whether the costs are realistic, and in order to make the scheme possible I feel that we shall either have to produce electricity at a very much greater efficiency than at present, or alternatively, electricity will have to be made available from some source other than the burning of coal. The figures given in the paper compare $2\frac{3}{4}$ tons of coke with 5 100 kWh of electricity. This makes the cost of heating by electricity £4 a year more than the cost of coke. Electricity must therefore be made available at $\frac{1}{2}$d. per kilowatt-hour. The author has perhaps conveniently forgotten any maximum-demand charge in making his calculations.

Mr. V. J. Simson: The author has stressed that the problem of space heating is that of conditioning the dwelling so that the body in it can have the rejected heat removed at an optimum rate.

I would like him to consider the problem as that of subjecting the body to treatment in order to make it feel comfortable and not primarily that of treating the dwelling. There is a subtle difference between these principles.

It is quite possible with efficient high-temperature radiant electric heating to make a person feel quite comfortable in an extremely uncomfortable dwelling, and I think the author will agree that this is different from conditioning the dwelling.

The author refers to the heat wasted if an electric fire stands in an open hearth. This may be large for certain types of fires, but for a correctly-designed high-temperature radiant fire it is not so. Many fires being sold in this country as so-called radiant heaters are very inefficient as such, and it is of the greatest importance that all types of electric heaters do function in the most efficient manner.

The usual criterion of radiant-type electric fires has been that of radiant efficiency, i.e. the percentage of total heat emitted as radiation. All this radiated heat is not necessarily directed in the best manner. For instance, some fires direct the main portions of the radiant heat into the floor or ceiling, and consequently do not produce heating comfort to users. A bowl fire is an example of high radiant efficiency with low comfort conditions for the user.

The author comments on high-level heating by the use of glass-enclosed elements. However, it is fairly well known that, with radiant heating, conditions should be such that a person using it does not have his head warmer than the rest of his body. It is difficult to see how picture-rail-level radiant heating can produce the maximum ideal comfort conditions without causing the head to be warmer than the feet.

Mr. J. Armstrong: Architects are now fully alive to the importance of providing both insulation and efficient appliances in houses, but they meet two serious obstacles. First, to most Englishmen a definition of "comfort conditions" will almost certainly include an open fire—and it is fairly safe to assume that the greater the comfort, the more inefficient will be the appliance; until the point is reached where the heat is constantly supplied by electricity somewhere in the background, and the comfort is supplied by a coal fire, as advocated by the author. Secondly, it is difficult to persuade clients to spend money on insulation, which is normally concealed in inaccessible places and the effect of which is not easily felt.

Mr. A. W. Bates: The author gives very little information and few suggestions for the existing 13 million houses in Great Britain whose U factor varies from 0·24 to 0·5. The figure of 0·075 is far less than the accepted standard for present-day house construction.

We should carefully consider the type of heating for these existing installations. The fundamental problem is that there is a much greater heat loss through structure and air change than has been mentioned in the paper. Secondly, it is often so costly to improve the thermal insulation that in older houses it becomes impracticable. For example, a 9 in brick wall has a U factor of 0·36, and to reduce this to the present-day value of 0·2 would cost approximately 10d. per square foot. Therefore it would appear unwise to attempt to maintain continuous heating in all rooms of the house, and for reasons of economy only the living room should be continuously heated. The other rooms can be heated as and when required.

Where the U factor is very low, the electric-heating installations of the low- or high-temperature radiation type forming the background heating and where necessary topped by some solid-fuel appliance are considered satisfactory. Where the U factor is high it is desirable on the grounds of fuel economy to have solid-fuel background heating and top up where necessary with some high-temperature radiant source. In Fig. 4 it can be seen that, in houses where $U = 2·75$, 0·1 ton of coal is consumed per annum for either electric or central heating, but in a house where $U = 0·4$, 4·1 tons of coal are consumed in a centrally-heated house and 5·4 tons in an electrically-heated house.

Low-temperature radiant systems installed in the higher-U-factor houses will not be so efficient as high-temperature radiant systems owing to large conduction losses through the walls and loss by ventilation. The most satisfactory method of heating rooms which are not continuously heated is by using high-temperature radiant heat. However, it is useless to employ any heating appliance which has been incorrectly designed, and in spite of high radiant efficiencies the radiation should not be directed to the most useful areas.

If the objection to burnt dust is considered important, the convective stream can be used to carry it up the chimney to the atmosphere. The presence of an electric fire in a hearth will, in fact, more than compensate for the increased ventilation it will cause, since it is possible to have a much higher rate of ventilation with high-temperature radiant-heating systems than with low-temperature ones.

The portability of the electric fire is not considered an adverse factor, and it is desirable in installations with a low capital cost, where comfortable conditions can be produced in any room of the house from the one appliance.

A well-designed radiant heater will have at its source an element operating at approximately 1 000° C, and it will have a radiant efficiency of approximately 70%. This radiation will be directed into the lower levels of the room and will produce a negative temperature gradient, which is the ideal condition for comfort. The author has mentioned that the ordinary thermometer is not a true measure of comfort, and where radiant heating systems are involved the comfort zone lies between 58 and 60° F, equivalent temperature scale, for adults engaged in light occupations. These conditions can be achieved at a much lower air temperature than with a convective scheme, and therefore the loss to air change is automatically reduced.

Mr. G. V. Sadler: Since we now have so much installed electrical generating capacity in the country to cope with peak-load demands, it is logical to make use of it for heating our houses during off-peak periods, and try to educate the house owner into improving the U value of his premises in order to make electric heating practical and economical.

From a psychological point of view a house should be thoroughly warm when the occupants get out of bed in the morning, and as human activity develops, the heating load can be reduced or even cut off until the evening, with perhaps a short boost period in the afternoon. This is practical with a properly

insulated house, and is exactly what the electricity supply authorities require.

Mr. B. France (*communicated*): The author deals with the problem of supplying all the heating services in a modern house, i.e. space warming, hot water, cooking, clothes drying, airing, etc. In my opinion none of these can be dealt with separately, and the author would have to go a long way to justify electricity for all services.

The crux of the paper lies in Section 9, where it is shown that, for an additional expenditure of 4s. 1d. per week, an Egerton house ($U = 0 \cdot 24$) can be converted to all-electric space heating, and thus one ton of fuel can be saved. The latest figures for electricity revenue from domestic consumers published by the B.E.A. show an average of 1·353d. per kilowatt-hour (also 1·327d. is shown for 1950–51, the period covered by the author), while the price of coke has advanced to approximately £5 per ton. The net effect is to advance the additional cost to 9s. 5d. per week. So long as the cost of electricity is tied to that of solid fuel, it will never make economic sense to a tenant, and the author's claims for the extra amenity are also open to doubt in view of the need to service the fan in the attic and vacuum-clean the heat exchanger periodically.

It is generally agreed that a U value of about 0·1 is essential for the use of electricity, and if it is to be attractive, from both a fuel-saving and an economic point of view, the cost of electricity must be decreased by improvement in the overall thermal efficiency of power stations and by stricter control to be exercised by the Area Boards and planning authorities of the electrical space heating to be permitted in new construction. If, as shown in Table 1, a net loss of revenue is suffered by the B.E.A. in the typical modern house, the sooner this drain is stopped the better are the prospects for electrical space heating in 20–30 years' time, when the overall thermal efficiency of power stations should have risen to 30%.

Mr. A. Lawton (*communicated*): The older houses, which still form the majority of domestic consumers, impose a great problem, since they are not provided with the modern fuel-saving grates on any large scale. The use of the open electric fire is almost universal and cannot be prevented. The effect of this heating load on the peak load has been over-estimated; not more than one-third of the load is transmitted to the peak. The load transmitted probably has an increasing load factor and is thus valuable since it extends into the trough. At the same time the cost of this heating is very great, and a contribution by the author to the solution of the problem would have been welcome.

The present coal-economy efficiency of electric heating is now officially stated to be 19%, against the 18% suggested by the author. Conditions have materially altered in recent years, and supplies of electricity are quickly becoming more adequate.

The revenue figure of 0·75d. per kilowatt-hour given in Table 1 is too low for present conditions, and it will be seen that the diversity of 1·5 is further questioned. The demands of the early-morning radiator and cooker are practically simultaneous, and furthermore the use of home fires during the morning factory peak is automatically limited by the cost to the consumer in the majority of cases. The few cases of high load factor cannot fairly be held against the use of radiators.

Mr. J. Newman Ellis also contributed to the discussion at Manchester.

[The author's reply to the above discussion will be found on page 390.]

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 20TH OCTOBER, 1952

Prof. E. W. Marchant: In the interests of fuel economy, every practicable device to increase the thermal efficiency of power stations should be introduced. With coal at the present price of 64s. a ton and with interest rates at 4%, it can be shown that it is an economic advantage to spend up to £10 per kilowatt installed to increase the thermal efficiency by 1%, say, from 30 to 31%, if the station is working continuously at full load. For smaller load factors the economic expenditure is, of course, lower. If the price of coal rises it will be economical to spend even more. I have grave doubts, however, whether the heating load will continue to increase as it has done during the last few years. The increase in demand has been reduced during the last six months, and the heating load seems likely to be little greater during the last six months of the year than it was a year ago. If the electricity supply industry is to flourish and continue to expand as it has done during the last few years I believe there will have to be some modification of the present tariff policy of the B.E.A. The basic charge in this area in 1938 was 0·3d. per kilowatt-hour, whereas it is now 0·85d. With a station of 30% thermal efficiency and coal costing 64s. a ton the coal cost is 0·32d. per kilowatt-hour. The average thermal efficiency of all the power stations on the Grid system is about 22%, and the coal cost then becomes about 0·42d., or about one-half the present basic charge. There seems no justification for the basic figure being nearly trebled. The B.E.A. regards itself as a generous benefactor that supplies electricity almost as a favour, but will that condition continue? In the long run demand will be governed by cost, and if costs are not reduced the demand will soon cease to increase at anything like the rate it has done during the exceptional period of the war.

Some provision should be made for supplying electricity at off-peak periods at a lower tariff. Water heaters used to be supplied at 0·3d. per kilowatt-hour, and there seems no reason why this should now be increased above 0·5 or 0·6d.; similarly with other non-peak loads which can be controlled from the power station. If a consumer is prepared to accept a supply only at off-peak periods he should receive some rebate on his charges, otherwise he will be driven to use other forms of heating. On the grounds of convenience, electricity has everything in its favour, but convenience may be purchased at too high a price.

Mr. R. W. Humm: As the author states, space warming by electricity need not coincide with peak supply periods if full advantage is taken of the thermal capacity of floors or walls for storage purposes. This has been fully proved in my own all-electric home.

The asphalt-covered concrete ground floors are warmed by carpet heaters in lounge, dining-room, hall and staircase; the latter under thermostatic control provides the main background heating for all rooms in the house. So effective is this heating that the temperature remains comfortable throughout supply peak periods when the floor heating is switched off. In the dining-room, tests with the electricity switched off showed a drop in temperature of only 1° F per hour over three hours from 64° F with an outside temperature of 40° F. In the hall, the carpet heater is loaded at 30 watts/ft^2, giving a surface temperature of 95° F, but in the dining-room and lounge, where the feet of the occupants rest on the carpet for long periods, a loading of 15 watts/ft^2 is allowed, which corresponds to a surface temperature of 85° F. Radiant electric heaters are employed for topping-up as necessary for individual comfort, and except in very severe weather, the radiant heat for continuous use rarely exceeds 500 watts in dining-room or lounge.

Ventilation is restricted to the minimum required to keep the atmosphere fresh and free from draughts. A centre inlet and

filter as advocated by the author for incoming fresh air is certainly desirable, since the amount of smuts and soot entering through open windows is considerable.

Space heating, including lighting, for this normal semi-detached house of 1 000 ft^2 floor area consumes 6 000 kWh per annum, which costs £23, including standing charges at the present rate of 0·85d. per kilowatt-hour. No special thermal insulation is employed for walls and ceilings.

The restriction of electricity for domestic use is quite purposeless except during supply peak periods. Householders who have all-electric houses do keep off the peak. Unlike the fuel-fire advocates, the all-electric house owner is electricity-supply conscious and does not need to bolster up the shortcomings of fuel fires with electricity at peak hours.

Mr. J. L. Carson: Would the author detail the method of deduction by which he reaches the conclusion that, if domestic heating were changed over from solid fuel to electricity, coal consumption would have to be 11 times the present consumption in power stations? Does he refer to the 4 million tons used for domestic supply, or the 15 million tons total consumption? I would like clarification of the statement that 30 times the amount of generating plant would be required.

The suggestion that walls should be heated to a temperature 3° F higher than that of the air seems to be a new departure. How is it intended to heat the walls to that extent?—and if they are so heated, surely the heat loss must be greater than if they were kept at a slightly lower temperature than the air temperature in the room. The walls are in position primarily to protect the room from outside draughts and to keep the heat in. By raising them to a higher temperature, the temperature gradient will be greater and the heat loss greater.

The author gives a coal consumption of 3·5 tons for the normal house built to the Egerton standard, i.e. $U = 0{\cdot}24$, and for a house designed for $U = 0{\cdot}075$ he gives a figure of 2·75 tons of coal per annum. Coal consumption for an electrically-heated house is stated to be 2·5 tons per annum when $U = 0{\cdot}075$, and it is assumed that 13 million tons of coal could be saved per annum at the rate of 1 ton per house by building to the better thermal specification and heating by electricity. If houses have been designed for $U = 0{\cdot}075$, the true comparison would be 2·75 tons for the equivalent solid-fuel consumption. This means a saving of only ¼ ton per annum for each house, or 3·25 million tons per annum.

I think that the development of electrical heating of houses will go on, but it will not be a matter of legislation. It is a matter of free choice, and the solution is stated in the first statement in the paper—an abundant supply of electricity at a reasonable price is necessary. I think that in the next few years, with the rising costs of other fuels, it will soon be found that electricity is the cheapest form of heating, and with the development of atomic energy which can be expected in the next 20 or 30 years, electricity will be the only method of distributing heat to the consumer.

Mr. W. Gilchrist: My investigation in this area indicates that the average domestic space heating load is a relatively small component of the domestic demand, and there is no conclusive proof that domestic electric heating is, in fact, 25–30% of the total demand, nor is there any clear indication—at least in this area—that this load is increasing.

Fig. 2 indicates that there is an increase in heating during spring and autumn, which has advantages in improving load factor and saving solid fuel, since the majority of this heating is for short-period use.

The author mentions variable temperature as being a feature of the English climate, but I wonder whether that is really serious. We require continuous heating, generally in one room only, from October to April. The variation in the other rooms is perhaps more in regard to occupation than temperature, and the most satisfactory way of dealing with the occupational variant is by the use of electric fires, which provide immediate comfort as and when required. I am interested in the author's proposals for using infra-red heating, and would like his views on the experimental work being carried out in this field.

In an effort to justify low-temperature heating, I think the author overstresses the dangers of fire and shock from electric fires, which he knows will now be provided with suitable approved guards. While I agree that better insulation of houses is desirable, if not necessary, I am doubtful whether the costs indicated in the paper are not lower than would be found in practice to achieve the degree of insulation recommended by the author.

I do not agree with the figures given in Table 1. For an average small house using the combination *EgC/E*, which purports to be a municipal house with solid-fuel background heating and electric topping up, the maximum demand based on the a.d.d. for a large area would be considerably less than 1 kW, as compared with 4·5 kW given in Table 1, and the heating consumption would be of the order of 600–800 kWh per annum, as compared with 4 100 kWh given in Table 1.

Mr. D. A. Picken: I do not think that the comparison of solid fuel with electricity, given in the paper, is quite fair. For a given national expenditure of coal twice as much heat can be produced in a room by solid-fuel methods as by electricity under present conditions. I am intrigued by the author's arguments that electricity can give comfort, but I think some of them are not well founded. For instance, he makes much of the ratio between convected and radiant heat. This depends almost entirely on the nature of the surface which is used, and it is very difficult to prevent housewives from using their own particular polishes which will completely upset the ratio. Similar effects can be arranged even with the low-temperature solid-fuel type of radiator, which can give quite a high radiant component of its output. The advantage does not lie entirely on the side of electricity.

I doubt whether the type of house that the author has in mind is going to be the house of the future, and I also doubt whether we can continue to afford about six, or even ten houses to the acre. We shall probably have to provide houses like those which have recently been built in Marseilles, where 400 dwellings are mounted on stilts. They occupy about the same space in an entirely different way, since they leave an enormous amount of space for playgrounds and pleasant surroundings and provide very much more amenable conditions with regard to heating.

Mr. A. J. Fairrie: At peak hours in the south of France the meter changes to another set of dials, and consumers pay an exceptionally high tariff. The system merits serious consideration in this country, because obviously for some years we shall have a shortage of generating capacity at peak periods.

Mr. G. H. B. Hicks also contributed to the discussion at Liverpool.

[The author's reply to the above discussion will be found on page 390.]

WESTERN CENTRE, AT CARDIFF, 3RD NOVEMBER, 1952

Mr. A. J. Dalton: In Section 3 it is stated that the proportion of low-grade slack is increasing because of exhaustion of thick seams and increased mechanical coal mining, and we may therefore expect a considerable expansion in the use of coal for electric

heating without economic embarrassment. It is important to realize that the National Coal Board also have ideas regarding slack, and that briquetting plant is being rapidly increased for the purpose of producing smokeless slow-burning fuel of consistent quality. I am interested in the author's suggestion that a radiator could be developed in the form of a vacuum tube enclosing an infra-red filament. This idea certainly has great possibilities.

In designing a floor-heating installation, the additional point should be made that the air temperature of a room heated in such a way could be quite a few degrees lower than that considered to be a comfortable temperature with a convected heat system, thereby reducing the losses through the fabric of the building.

The author seems to have omitted consideration of the fact that, throughout its life, a room may be carpeted or otherwise, according to either the pocket or taste of the occupier, and it would seem desirable that this should be taken into account when designing a heating installation. In the event of wall panels being used, it would seem that the suggested Treetex and Celotex would, in effect, take the place of a carpet and blanket the heat from the room. Perhaps the author could suggest some alternative type of wall construction.

With regard to the manufacture of slow-burning smokeless fuel which appears to give rise to the minimum of grit emission from the ordinary domestic chimney, most of the arguments concerning tall chimneys would lose their force if we were not able to secure business in competition against the new solid fuels.

The figure of 8 000 ft^3 given in Section 15.1 would appear to provide a change of air in the whole of a normal house once every hour. Does the author consider that this is really necessary when possibly there may be only two people in the house and one room occupied at a time?

Mr. D. G. Gwyn: In attempting to make out a case for basic domestic heating by electricity, the author has not paid sufficient attention to the comparative costs to the householder of obtaining heat by the alternative methods of solid fuel and electric heating. Even with anthracite or similar high-grade fuel costing £8 per ton, a modern closed-type stove at 60% efficiency would yield approximately 8 400 B.Th.U. for 0·86d. Electricity at 100% utilization efficiency would need to be sold at 0·35d. to obtain an equivalent amount of heat at similar costs, and therefore, for basic winter heating, whilst electricity is undoubtedly the most convenient medium, it is certainly not as cheap as solid fuel when correctly used. However, heating by electricity has very many advantages if applied for partial use during spring and autumn months. For early-morning and evening heating—even at present-day costs to the consumer—it is much cheaper than kindling a solid-fuel fire for short periods. The use of electric heating during these periods would also cause no drain upon the winter peak-generating availability.

In Table 1 the annual maximum-demand cost is given as £4·125 per kilowatt, and whilst this was the bulk supply cost to Area Boards at the time the paper was written, it cannot be conceded as a reasonable measure of maximum demand costs for electric heating, if the principles advocated by the author were extended for general use in domestic premises. Actually, any conversions to the author's methods must be regarded as requiring incremental power, associated with present-day costs. With power stations costing more than £60 per kilowatt, and transmission, distribution, servicing and metering costs approaching £80–90 per kilowatt, interest charges alone, upon incremental demand, would be approximately £5·6 per kilowatt. The figure referred to by the author was the average resulting from the very high proportion of pre-war capital equipment then in use in the supply industry.

Mr. E. W. Faithful: I consider that Table 1 is subject to question, as in U.R.R. report No. 4 the average consumption of electricity for space heating, obtained from sampling tests, was given as 2260–2800 kWh per annum, when the heating load was over 5 kW, and under 1 000 kWh per annum when the load was up to 3 kW. From a study of all-electric flats by Schiller,* the total average consumption for all purposes was given as 5 900 kWh per annum, and for space heating alone it was given as 2 000 kWh per annum. The figures given in Table 1, which were no doubt based on Egerton standards, would not be reached by the average consumer, who, whilst using adequate heating in the living rooms, would be satisfied with a much lower standard of comfort, and would reduce the heating in bedrooms, passages, etc., until the final consumption would conform closely to that shown in the U.R.R. report. This is confirmed by the tests carried out by Schiller. I have found that, without any radiant heating, a room temperature of 70° F is required for comfort conditions, whereas with a reduced amount of background heating and a little radiant heat, as given by a 1 kW electric fire, a room temperature of 63° F produces the same comfort conditions with a saving in fuel.

Mr. C. H. H. Pease: As domestic heating is mainly concerned with comfort I feel that one very important factor is the humidity of the atmosphere. This applies equally to any form of heating, but if it is considered preferable to use electricity, has the author any suggestions to make on the possibility of controlling the humidity?

Mr. E. Arthur: In Section 12 it is stated that the space-heating load would result in improved load factors on generating stations. This seems to be entirely contradictory to the conclusion reached by the British Electricity Productivity Team which visited America. In their conclusions they state that the complete absence of the space-heating load in America contributes to the much higher load factor there, and makes possible a more economical use of plant.

Mr. W. Hill: The author states that continuous heating is inefficient, but on the other hand, he refers to the need for wall heating. Surely continuous heating gives the most comfortable result. If one enters a room which has only just been warmed, although the thermometer may indicate a high temperature, the cold walls make it feel really uncomfortable, whereas a much lower temperature is more comfortable if the walls are warm.

The authors appears to imply that draughts in existing houses could be overcome by the use of electricity, which would obviate the necessity for chimneys, etc., but I suggest that in many rooms the draught is created more by the windows, particularly those of thin glass, which allow circulating currents in the room.

With regard to the use of the combined stove for cooking, water heating and space heating, I suggest that the small householder cannot afford three separate appliances, and that with the great increase in the output of boiler fuels, partly owing to the extra small coals produced by mechanization in the mines, there will be a tendency to use these, although they have their disadvantages.

Mr. R. B. Rowson also contributed to the discussion at Cardiff.

[The author's reply to the above discussion will be found on page 390.]

* SCHILLER, P.: *Electrical Review*, August, 1951.

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 25TH NOVEMBER, 1952

Mr. G. A. Farthing: By its nature floor heating is more suitable for the thermal-storage background type of heating. The advantages claimed for this type of heating are:

The heat is applied in a room in the right place, i.e. evenly all over the floor, and it radiates upwards.

Since charging can be done at off-peak times, it can be used to improve system load factor.

The disadvantages are:

If it is to be economic, the house must be insulated to a high standard.

Unless there is considerable expenditure on insulation, there must be a downward heat loss.

Any kind of floor covering adversely affects the efficiency, since it raises the temperature of the floor, thereby increasing downward losses.

In order to make the best use of its off-peak characteristics there must be some form of control other than that of the householder. This necessitates the use either of time switches or some form of remote control in the hands of the supply authority.

Thermostatic control on low-level radiant heating of this type does not appear satisfactory; e.g. there may be a reasonable degree of comfort in a radiant-heated room even though the air temperature is below the level normally required for comfort.

The disadvantages, particularly in view of the initial cost, appear to outweigh the advantages. It is agreed that, whatever form of heating is used, thermal insulation will, from the point of view of running cost, be advantageous.

It would appear that, with the present relative costs of fuel and unless some other form of background heating with storage properties using electricity as a fuel can be devised, there is not much future for background heating by electricity. With regard to floor heating, from a heating point of view, the floor is virtually an outside wall of the house, and as in modern building practice, chimney flues are not built on outside walls but on inside ones in order to conserve heat, would it not therefore be better to put the electric heating elements in the ceiling of the room to be heated, when any waste heat would be usefully employed in keeping, at least, the upstairs rooms aired? The objection to ceiling heating raised in Section 5.3, namely conduction loss, then appears to be an advantage. In order to employ ceiling heating a certain amount of special plastering is required, and in place of wooden joists and floor boards, to which there might be some objection, flooring with concrete beams with air spaces could be employed. The additional cost would not be as much as the author suggests for the cost of insulating the concrete floor raft for floor heating. The ceiling could be designed to have the desired amount of thermal storage.

Ceiling heating also has the following advantages:

Any floor covering in the room above increases its efficiency so far as the room below is concerned.

Radiation from the ceiling is unobstructed in contrast to that from the floor which is covered with carpets and furniture.

There is improved warming of walls and upper (working) surfaces of chairs, tables, etc.

To the popular mind there are certain objections to ceiling heating, i.e. radiant heat from above, and it is appreciated that some electrical versions of this form of heating, such as small-area high-temperature panels and even larger-area lower-temperature built-in types of panel, have not been entirely satisfactory. There are, however, many perfectly satisfactory installations of ceiling heating where large areas of low-temperature heat are used, i.e. the whole of the ceiling being heated, and the comfort factor of this form of heat appears relatively great. In any case such floor or ceiling heating is necessarily of a background character and would in all probability be augmented by small radiant heaters at floor level when necessary.

Would it not be possible to employ a control switch of the nature of a Simmerstat in order to enable the user accurately to set the degree of heating required to a maximum, depending upon the loading of the heating elements? In a number of installations using this type of control there would be a diversity between the impulse times of the automatic switches themselves, and this would have the desired effect of lowering the after-diversity demand, i.e. the improving of load factor.

The following temperature readings were obtained in a room heated from the ceiling. It is appreciated that it is not representative of domestic conditions, but there appears to be no reason why similar results should not be obtained in smaller rooms.

The room is approximately 20 ft wide and 80 ft long, and the ceiling is 10 ft high. With the outside temperature at 40° F, the ceiling temperature of the room was 74° F and the floor temperature 66·3° F. The air temperature at 1 ft below ceiling level was 67·6° F, and at 1 ft above floor level it was 64·8° F. Up to 7 ft above floor level it was practically constant at 65° F. The temperature of the inside walls ranged from 68·7° F at 1 ft below ceiling level to 66·1° F at 1 ft above floor level. These temperature readings indicate clearly that the radiant heat from the ceiling has the desired effect of heating the walls and floor. At the same time the air temperature at working level is adequate, and contrary to expectations, the temperature gradient is very low.

Mr. J. T. Scott: The author considers that the standards of insulation proposed by the Egerton report are not sufficiently high. With solid-fuel heating, an increase from an overall value of $U = 0 \cdot 24$ to the author's figure of 0·075 saves, according to Fig. 4, about $\frac{3}{4}$ ton of coal per annum, or say £3 7s. 6d. From Table 2 the investment required to achieve this is £145, which, with the addition of labour and overhead costs, will be increased to say £170. The annual return is therefore about 2%. This suggests that the Egerton standard is reasonable for solid-fuel-heated houses. With the all-electric house the return is about 6·5%, which makes the improved insulation more worth while.

With regard to controlled ventilation and the heat exchanger, this proposal makes the equivalent coal consumption for the all-electric house fall away sharply, as shown in Fig. 4, when the insulation is increased above $U = 0 \cdot 1$. Whilst 8 000 ft^3/hour appears adequate in total, I doubt very much whether it can be directed to the different parts of the house with sufficient flexibility.

Electric floor heating is attractive if, as the author suggests, it can be designed as a heat-storage system taking its supply only at night. Unfortunately Sections 9.2 and 9.3 cast doubts on the possibility of restriction to night loading. I cannot accept the assertion that, as a continuous load, it would improve the load factor on generating stations. This would only happen if the diversity quoted in Table 1 were achieved, and in view of the statement in Section 6 that the demand in cold weather would be about 1·5 kW continuously, a diversity of 1·5 seems impossible.

One of the important features of a relatively unknown system of the type proposed is that, before it is adopted for general use, it must be made absolutely reliable and, in addition, it must not involve heavy maintenance costs. In this connection, some modern solid-fuel installations leave much to be desired, but it is unfortunate that the author casts doubt on the reliability of his proposals by providing an emergency coal fire.

In Table 1, I think that the author has been unfair to the second house. The full maximum demand of 9 kW will only be achieved on limited occasions, since most occupiers of council houses will be reasonably economical and will not require bed-

rooms to be heated at the same time as the living-rooms. With a diversity factor of $1 \cdot 5$ the maximum demand should not be more than say 6 kW, but the consumption also appears high in comparison with results calculated from Fig. 4. The diversity for the insulated house is probably too high, and the distinction between the two types of house given in the Table is highly conjectural. Furthermore, it does not take account of distribution costs.

Mr. J. R. Hanchett: The author does not mention electrode boilers. I know of a number of installations where these are very satisfactory, particularly when the plant has to run continuously with the minimum of supervision. There is a great saving of labour, and it is a form of hot-water heating which should be further investigated.

Mr. J. L. Ineson: The author suggests that the way to test his findings would be to conduct large-scale trials on houses built to his specification. This would be an expensive job. In statistical work it is common to reduce an experiment to a manageable size by selecting a sample which is a copy, on a small scale, of the large mass of material being examined. The author could test the accuracy of some of his assumptions by building one or a number of small model houses and conducting tests on them. This is a commonly used method of measuring the behaviour of large, expensive objects, and the theory involved in drawing inferences has been worked out and well tested.

Mr. J. G. Craven also contributed to the discussion at Leeds.

[The author's reply to the above discussion will be found on page 390.]

SOUTHERN CENTRE, AT PORTSMOUTH, 3RD DECEMBER, 1952

Mr. G. R. Lomax: In Section 7 the author is rather unfair in his comparison. For the solid-fuel-heated house the mean temperature is shown as being 5° F higher than that of the electrically-heated house. If this is due to the difficulty of controlling temperature with convected air delivered to the bedrooms, it is feasible to use convected air from the appliance in the downstairs rooms.

In Section 8 there is little point in showing a hypothetical gain of 13 million tons of coal for electrically-heated houses as against solid-fuel-heated houses when favourable heat-insulation standards are assumed for the former method. The apparent real gain is in comfort and cleanliness, but, of course, there is a possibility that the load factor on generating-station plant may be enhanced. The capital cost of such gains is an addition of 16% to the cost of the house, which is a considerable addition by any reckoning.

There is much to be said for flexibility in house heating where possible. I have a modern grate, which not only provides radiated and convected heat but heats the water as well. There are also electrical tubular heaters, gas fires, and latterly a water-to-air heat pump with an output of about 18 000 B.Th.U. per hour. Thermal insulation is confined to 4 in of fibre glass between the ceiling joists, and draught prevention to phosphor-bronze strip on the front and back doors.

Built-in air ducts have much in their favour as a means of distributing heat. They are very cheap to install, they can be fed by a variety of heat sources and they enable heat to be either concentrated or diffused at will.

As heat sources for a duct system, I can foresee the heat pump as being a likely partner to the down-draught solid-fuel furnace. The use of the heat pump will receive real impetus with the wider use of refrigerators and a satisfactory solution to the problem of finding a cheap method for recovering low-grade heat from the ground.

A domestic refrigerator with a larger motor-compressor unit designed to have an output of 5 000–6 000 B.Th.U. per hour at a performance coefficient of about 3 might involve an increase of 20–30% in first cost. The condenser would be permanently fitted in the duct system, and an extension to the evaporator would be buried in the garden.

A useful operational plan for these two heat sources would be to use the heat pump during the milder parts of the four months October, November, March and April, and the solid-fuel furnace in the colder months of December, January and February. I think that such a system would prove favourable in first cost, operational cost and coal economy, and would provide the requisite measure of flexibility which is so desirable at present.

Mr. E. A. Logan also contributed to the discussion at Portsmouth.

[The author's reply to the above discussion will be found on page 390.]

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 21ST JANUARY, 1953

Mr. A. G. Thomson: I would like to give the results of some measurements made on a solid-fuel installation at my home. Two enclosed (but openable) stoves are involved, and they are installed in the adjacent rooms A and B.

Room A. 27 ft × 17 ft × $13\frac{1}{2}$ ft: 465 ft^2: 6 300 ft^3 (approximately).

Room B. $18\frac{1}{2}$ ft × 15 ft × $13\frac{1}{2}$ ft: 274 ft^2: 3 700 ft^3 (approximately).

This gives a total of 10 000 ft^3.

Since these are the results of measurements on the installation, they apply to both stoves working at once and operating continuously for 24 hours a day. The fuel used is exclusively domestic "ration" coal taken in the form of "doubles" and costing (last bill) £4 6s. 11d. per ton. The average weekly consumption over 20 consecutive weeks was 144 lb, and hence the weekly cost was 5s. 7d. This represents, with electricity costing $\frac{7}{8}$d. per kilowatt-hour, approximately 11 kWh per day, which is hardly adequate to warm one room. Over one month (mid-December–mid-January) temperature measurements were made showing that in room A, which is not used every day, the mean maximum and minimum temperatures were $63 \cdot 5$° F and 57° F respectively, while the absolute maximum and minimum temperatures were 70° F and 53° F. The corresponding figures for room B were 68° F and 59° F, and 70° F and 56° F, respectively. The total time for clearing, stoking and fetching coal was measured only over two weeks; the figure obtained was 65 min per week.

It is expected that, over about 34 weeks' operation in the year, both stoves will consume two tons, which is less than the normal domestic issue; and no coke, anthracite or other fuel has been used.

It is thus felt that for many existing houses, where $U > 0 \cdot 1$, a solid-fuel installation offers another if not the logical solution to the problems of space warming.

[The author's reply to the above discussion will be found on page 390.]

NORTH STAFFORDSHIRE SUB-CENTRE, AT STOKE-ON-TRENT, 6TH MARCH, 1953

Mr. L. Goodall: Some success in the space-heating field has been obtained on the commercial scale, particularly where special cleanliness and minimum of attendance are of value. This has been on the thermal-storage system, with a very low price per kilowatt-hour for load restricted to night hours only. The author approaches the subject from a different angle, and proposes to reduce the cost of electric heating by using greatly increased thermal insulation of the house itself to reduce consumption. While some progress has already been made in this direction, a very much higher standard is required to reach the conditions necessary for economic heating by electricity. It is considered that the methods shown in Fig. 3 would be such a departure from traditional construction that there would be considerable opposition to their use. It might be worth investigating the use, for the inner course of a normal cavity wall, of some of the exceptionally good insulating bricks developed for electric kilns. Is the council housing estate the best field for initial experiments? Would it not be better to start with privately-built houses where the extra cost can be more easily offset?

Table 1 shows clearly the difficulty of obtaining the heating load. With a house improved to $U = 0 \cdot 24$, the cost of electric heating would be £57·8. The cost of £15·9 for the house having $U = 0 \cdot 075$ is probably the limit obtainable from council houses, as water heating and cooking have still to be added. No mention is made of the competition from gas, which would also benefit from the reduction of heat losses and probably offer a cheerful fire.

[The author's reply to the above discussion will be found overleaf.]

NORTHERN IRELAND CENTRE, AT BELFAST, 14TH APRIL, 1953

Mr. W. McCullough (*communicated*): Emphasis is laid on improved thermal construction, but the trend of modern architecture is in the opposite direction, i.e. flat roofs and considerable glass surfaces without much thought being given to double glazing. Examples of this can be seen in modern schools and private residences at present being erected. This type of construction in no way approaches the somewhat idealistic value of 0·075, and in fact, is much higher than the overall U value of 0·24 mentioned in the Egerton Report.

While the policy of improved thermal construction is sound and should be vigorously pursued, at the same time a short-term policy must be adopted in order that the electricity industry may have its share of space heating.

With regard to the economics of space heating for the householder, there has never been a better opportunity to present the case for electricity than exists at present, as is evidenced by the increasing number of space-heating installations, not only in residences, but throughout industry and in institutions.

The case for electric heating would be better served by research into the efficiency of solid-fuel-burning appliances so glibly quoted by the respective manufacturers and accepted in good faith by prospective clients. There is no doubt that on test beds, with the combustion expertly controlled by careful air adjustments by means of accurate instruments and expert stoking, efficiencies of up to 65% are attainable. But these efficiency tests bear absolutely no resemblance to actual working conditions where banking down both night and day with a black fire is the only careful attention a solid-fuel appliance ever receives. For example, a particular hospital installation was in use 24 hours per day and stoked by an alleged expert, and the measured overall seasonal efficiency was of the order of 15–20%.

In an Address by Mr. J. G. Bennett, Director of the British Coal Utilisation Research Association, a few years back, the conclusion was reached that, from the point of view of coal conservation, it is immaterial whether gas, electricity or coal is used for heating purposes. I am not aware of any serious challenge to this conclusion.

Messrs. F. Johnston and **F. H. Whysall** and **Major J. E. Jones** also contributed to the discussion at Belfast.

[The author's reply to the above discussion will be found overleaf.]

SOUTH-WESTERN SUB-CENTRE, AT TAUNTON, 24TH NOVEMBER, 1953

Mr. P. S. Grant: The author appears to be confident that, in the event of his proposal being adopted on a large scale, the improvement in the thermal efficiency of B.E.A. generating stations could be continued, and the Area Boards could continue to sell electricity at the present general level of charges (assuming stable fuel and labour costs).

Since the load imposed by background space heating, as described in the paper, would be a winter load with a load factor of only 36%, it seems probable that the costs both of generation and distribution would be increased.

Mr. A. M. Donald: The question of cost to the user is of major importance, and I would make the following comparisons from figures given in Table 1 of the paper. This comparison is based on a normal seven-room dwelling house and a price of 1d. per kilowatt-hour.

Type of House

E.G. A–E 18 500 kWh per annum. Average cost per week: 29s. 6d.
Heating per room over this period: 310 watts (approximately).

1 *A–E* 5 100 kWh per annum. Average cost per week: 8s. 2d.
Heating per room over this period: 84 watts (approximately).

Compared with this, a modern solid-fuel central-heating stove would appear to be of value, as it will raise and maintain a general temperature of 15–20° F above the outside temperature and allow for at least one change of air per hour, for the consumption of 28 lb of coke per day (colliery), which at the present price of £6 18s. 0d. per ton, costs 12s. 1d. per week, or the equivalent of 145 kWh of electricity.

Usually little additional local heating would be required provided that the roof space had an adequate insulation, the design and position of the house was good, and reasonable care was taken in the choice of the building material used in general construction.

[The author's reply to the above discussion will be found overleaf.]

Messrs. F. C. Winfield and **F. W. Watson** took part in the discussion before the North-Eastern Centre at Newcastle upon Tyne on the 23rd February, 1953.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. D. H. Parry (*in reply*): I reply to the points raised by individual speakers under separate headings.

Mr. Phillips.—Good heat insulation is worth while for all fuels, but it is far more economic for electrical heat than for combustible fuels. Electricity is expensive, but accurate temperature control ensures a saving of consumption. Furthermore, reduced heat losses mean a smaller mass of material necessary for heat storage if electricity is taken off the peak. Heat storage sufficient to cover switching out for some hours also delays temperature build-up, and again, the heated mass can be kept to the minimum by good insulation. Solid-fuel stoves sometimes go out, but they are inherently less flexible in recovering loss of temperature.

The life of a cable buried in concrete is not yet known, but I would expect it to equal that of the house. Cable faults do occur, and I suggest only a shallow burial under soft concrete so that a faulty cable could easily be renewed.

Mr. Phillips and other speakers question the cost of a well-insulated house. The difficulty is that architects are not encouraged to design such houses as a whole, but rather to add bits of insulation to a conventional design. In fact, heat insulation ought to be the prime object of design. Some well-insulated and inexpensive buildings are prefabricated in this country for export. They are not, of course, entirely suitable for weather conditions in this country. Prefabrication is perhaps necessary, but it implies mass production and demands much experiment beforehand. Cheap materials are available, and it should be quite possible to produce a well-insulated house at no more than 16% greater cost than the kind of house we are building at present.

Ventilation and the heat exchanger may raise doubts in the minds of some engineers, but many silent and reliable fans are available, and I am sure that measured ventilation is necessary to get the best results from an all-electric house. The heat exchanger is worth while with first-class insulation, but it may appear unattractive although practicable. A possible alternative is heat recovery by using the domestic refrigerator as a heat pump.

Mr. Jones.—Whilst I agree that high-temperature radiators provide a very efficient source of comfortable warmth, it still appears that they are largely responsible for the severity of the early-morning peak load.

Dr. Mitchell.—A considerable amount of heat is rejected from power stations, but it is at a low temperature. The heat would have to be rejected at a higher temperature to be useful in residences, and this temperature loss is worth more to the power station than the sale of low-grade heat through an expensive distribution scheme.

Mr. Moore.—It is customary to produce central-heating plant of a capacity designed for an ambient temperature of 32° F. One thermostat on an inside wall of the living room should give reasonable results in a small house. If the heat exchanger became choked it would soon be obvious, but nobody would be poisoned as sometimes occurs with combustible fuels.

Mr. Coleman.—Consideration of commercial heating was avoided in order to keep the paper to a reasonable length.

Mr. Clarke.—Tribute should be paid to Mr. Grierson and Dr. Bedford for their early work on comfort heating. The query on topping-up by solid fuel is not understood, since many householders light a coal fire even when their house is adequately warmed.

Mr. Morgan.—The fan consumption is included. The opening of windows is not common in cold weather, and if there were positive ventilation it would soon become uncommon at all times with a saving not only of heat but also of dust infiltration.

Mr. Chilvers.—A set pattern is followed to secure cheapness in first cost, but the proposed method of heating does allow flexibility. A thermostat can be adjusted downwards if the cost of heating is too high, but a continuous-burning solid-fuel appliance is not so easily controlled. The costs of all fuels appear certain to rise continuously, but we can confidently hope that the margin of costs between electricity and combustible fuels will steadily diminish.

Mr. Simson.—The speaker emphasizes the importance of conditioning the body rather than the building, and I agree about the effectiveness of high-temperature radiation. However, a substantial amount of background heating is essential, and it may reduce maximum demand.

Mr. Armstrong.—Englishmen soon get used to the absence of a coal fire, and in a few years' time they may be compelled to by the scarcity of suitable fuels.

Mr. Bates.—The *U* factor in an old house cannot be improved without great expense, which is a good reason why we should insist that new houses be built to standards which will be economic in future years. It may be too expensive to insulate the walls of an old house, and radiant fires are therefore a boon; but comfort conditions can be cheaply improved by roof insulation, and the fitting of double-window casements may also be worth while.

Mr. France.—The speaker wants the B.E.A. to control electric space heating when it is unremunerative. Fortunately, perhaps, this is impossible. Electric space heating is a most useful service and is often very profitable, but experience has shown that attempts at control restrict the profitable but not the unprofitable use of electric heating. The paper emphasizes the need to look ahead so that the profitable use of electric heating will be fostered.

Mr. Lawton.—The speaker suggests that old houses are the great problem, but unfortunately that is not so. We are building 300 000 modern houses a year, but although they are equipped with modern fuel-saving grates, they impose as large a space-heating demand as the old houses.

Prof. Marchant.—I heartily endorse the speaker's plea for low electricity prices, and particularly for an attractive off-peak tariff. Most Area Boards are now introducing off-peak tariffs, and consumers who use them will assist in bringing down prices to all consumers.

Mr. Humm.—The speaker's experience with carpet heaters is most interesting, but I would imagine that heavy wear would cause short-circuits and entail the risk of fire.

Mr. Carson.—I do not know whether the Egerton and Simon Committees ever contemplated a complete change-over from solid fuel to electricity, but had they done so these figures represent the kind of speculations made. They were aiming at the standards of comfort obtainable from 50 million tons of coal burned in solid-fuel appliances at 50% efficiency. They would have assumed the coal-economy efficiency of electric heating to be one-third of this, which would require 150 million tons of coal to be burned in power stations in addition to the existing consumption, and they would have expected the load factor to drop to one-third of the 1938 figure, which gives figures of 11 and 30 times, respectively. From a later paragraph it is made clear that these speculations were out of date by the time the paper was published.

Both wall and air temperatures influence comfort, but a rise of wall temperature of 3° F may permit a fall in air temperature of 5° F, and the saving of ventilation loss will more than compensate for the greater loss through the walls.

Mr. Gilchrist.—With reference to Fig. 2 and the increase in heating during the spring and autumn months, the speaker points

out the advantages in improving the load factor. Unfortunately, on several occasions in these seasons, the B.E.A. has been short of plant. The summer is used for the annual plant overhaul, but the time available is increasingly curtailed at each end by the risk of heavy loads for heating.

Mr. Picken.—The speaker may be right about the future policy of housing in this country. Six or even ten houses to the acre means an excessive cost of electrical and other services, and this arrangement may be superseded by large blocks of flats. These would introduce a set of new problems not necessarily adverse to the use of electricity for house warming.

Mr. Fairrie.—Selective metering for peak hours raises a number of special problems rather outside the scope of the paper, and it would be most satisfactory if peak-load problems could be solved without recourse to special metering.

Mr. Dalton.—It is agreed that an important aim of floor heating is to provide comfortable warmth with moderate air temperatures, thereby reducing losses through the fabric of the building. It wall heating is employed there seems no reason to cover the panel with an insulating layer. With regard to ventilation, individual tastes vary considerably, and a generous figure was allowed. It should not be difficult to devise simple methods of control when only one or two persons are in occupation.

Mr. Gwyn.—The comparative costs of heating from anthracite and electricity are more unfavourable in South Wales than in other parts of the country, but even there I believe that the difference will gradually become less whilst the amenity value of electricity will increase. The increasing proportion of high present-day capital costs occurs in mining anthracite perhaps more than in generating electricity.

Mr. Faithful.—It is generally agreed that Egerton standards of comfort are somewhat excessive and are not desired by the majority of households, particularly those who make good use of radiant fires. They were adopted as a standard of comparison for the preparation of Table 1.

Mr. Pease.—In general, experts on domestic heating agree that conditions in this country do not warrant special control of humidity. Uncomfortable dryness results from the excessive use of hot air and unpleasant humidity from deficient ventilation, and a satisfactory condition is achieved by a proper proportion of radiant and convective heat and measured ventilation.

Mr. Arthur.—The Productivity Team reported the greater use of shift working in American industry and also the extensive use of summer air-conditioning, both of which favourably influence the generating-station load factor. I do not feel competent to advise on whether electric space heating is appropriate to conditions in many parts of the vast North American continent, but in this country it is a most useful service which could improve the plant load factor if its use were properly planned.

Mr. Hill.—All kinds of heating—and particularly continuous heating—are inefficient in the sense that coal is consumed, but wall heating is effective in giving comfort. Windows do cause circulating currents, but the actual leakage of cold air is more serious if there is a chimney. I suggest that the combined stove is satisfactory only if it is an expensive model and fed with a good fuel and not the product of mechanized mining.

Mr. Farthing.—There is much to be said for ceiling heating in a well-carpeted house, but there would still be a need for floor insulation. Mechanically it would appear easier, and therefore cheaper, to support elements in the ground rather than suspend them in the ceiling. A heated floor does give a better temperature gradient in a living room, and far more continuous heat is necessary in the living room than in the bedroom. I believe that these considerations tip the balance in favour of floor heating.

Mr. Scott.—The speaker asks whether night loading only is practicable, presumably with reference to Section 6 of the paper. A house in which the temperature would not fall noticeably in 12 hours requires a considerable mass for heat storage, and might prove unsatisfactory in the hands of an occupier who liked excessive ventilation. Much large-scale experiment is therefore necessary before a suitable design can be shown to be economic.

The provision of an emergency coal fire should cast no doubt on the reliability of electric heating. It is the usual practice in central-heating installations to design for an ambient temperature of 32° F, but every few years a period of severe weather occurs when lower temperatures prevail and comfortable conditions cannot be maintained without supplementary heat. It is sound economic practice not to design for severe weather conditions, but the use of portable electric appliances in such conditions should be discouraged.

Mr. Hanchett.—Electrode boilers have their use in large buildings, but the paper is mainly concerned with domestic premises in which appliances are required by the million.

Mr. Ineson.—The unknown factors in electric house warming are mostly concerned with human problems, namely:

(*a*) Can architects design a pleasing and economic structure with an unusual amount of insulating material?
(*b*) Can builders fabricate such a building without excessive labour cost?
(*c*) Will the characteristics of the well-insulated house suit the living habits of ordinary people?

Mr. Lomax.—I agree with the advantages of flexibility in house heating, and one objection to the use of convected air is its inflexibility, particularly if the stove also supplies hot water. The stove, if powerful enough for severe weather conditions, will produce excessive temperatures in mild weather, and good insulation aggravates these conditions. The heat pump is still more inflexible, because the output falls sharply in cold weather. Flexibility can always be obtained by multiplying the number of appliances, but at too great a cost for the standard house.

Mr. Thomson.—The speaker seems very fortunate in his heating arrangements. I suggest that his results are unique, and that the vast majority of users of solid fuel cannot attain such success.

Mr. Goodall.—Much investigation is certainly necessary in order to produce any radical departure from conventional methods of house warming. The greatest saving is likely to come from standard houses built by the million. The extra expense of the well-insulated houses lies not in the materials but in the methods of construction, and economy must therefore be sought in mass production. The privately-built house is hampered by the cost of architectural work, such as a pleasing elevation, and the architect tends to neglect improvements not obvious to the eye.

I do not think that gas is a serious competitor for whole-house heating. It is very expensive, possibly because the peak-load problem is more serious for gas than for electricity.

Mr. McCullough.—The paper is largely concerned with small residences of largely standardized type. We are constructing some 300 000 of these a year, which thus add over a million tons of coal a year to the annual consumption. I do agree that far too extravagant claims are made for the efficiency of modern solid-fuel appliances.

Mr. Grant.—The most valuable load on generating stations is that for lighting in winter, and it is necessary to have in service more plant in winter than in summer. During the night more than half the plant is unused, and it is available for a heating load without additional capital or labour cost.

Mr. Donald.—The speaker gives an interesting comparison of the costs of electric heating quoted in the paper with that of a modern stove, but he does not comment on the dirt and on the labour required to maintain the stove in use.

DISCUSSION ON

"INHERENT CURRENT, VOLTAGE AND SPEED CONTROL IN DYNAMO-ELECTRIC MACHINERY"*

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 8TH APRIL, 1952

Mr. E. L. N. Towle: Although, as the authors state, the Kramer generator is not now used as a constant-current generator, it is used in a number of applications to give inherent load limitation of the prime mover. A typical instance of this is Diesel-electric propulsion with Ward Leonard control. In order to limit the engine torque, the Kramer generator is provided with reversed series turns to give an m.m.f. equal to the self-exciting field, leaving all the excitation to be supplied by the separate field. With such a machine, a typical characteristic of which is shown in Fig. A, the series winding should

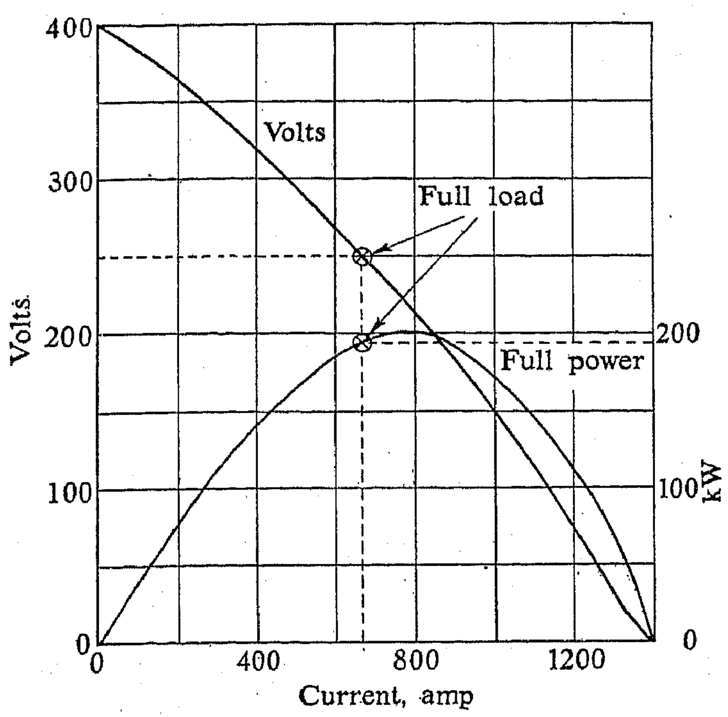

Fig. A

be adjacent to the pole tip. It will be apparent that the short-circuit current will be determined by the ratio between the m.m.f.'s of the reversed series turns and the separately-excited field. A rapid change in current in the separate field causes the generator to respond slowly on account of induced e.m.f. in the self-exciting field so that the generator can be used as an inherent load-limiting machine for bridge control of Diesel-electric propulsion systems. One precaution necessary is to prevent a sudden change of external back e.m.f. or load, since, in this event, although the stable characteristic is as shown in the Figure, the transients are limited only by the inductance of the circuit. For this reason it is normal practice to use motor-operated rheostats when using Kramer generators for twin-screw Ward Leonard control where the propulsion-motor fields are varied simultaneously with the generator fields. Thus a rapid movement of the bridge controller is translated into a comparatively slow change of motor field and overloading is avoided. A typical diagram for this scheme (excluding the motor-operated controllers) is shown in Fig. B.

The authors state that the Austin system holds the current

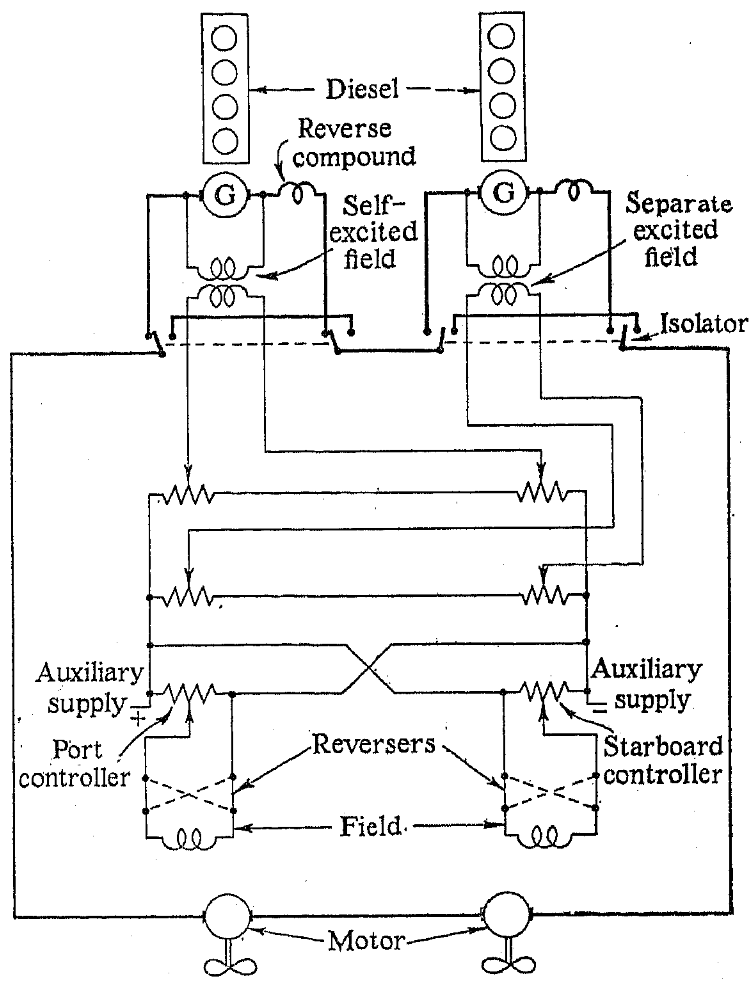

Fig. B

constant to within $\pm \frac{1}{2}\%$ and that breakdown time is 1/25 sec. If this is so it would appear from the oscillograms in Fig. 4 that the system has a natural oscillation frequency of approximately 50 c/s. This is very much higher than I should expect for a 160 kW machine. I know of a 450 kW machine for which the breakdown time is approximately 1 sec with 2·5 times field forcing on the metadyne exciter.

Another point which is not clear is how the load was removed from the machine. It seems from the statements in Section 2.2.2 that the machine was suddenly short-circuited. I should like to know if such was the case and if the machine was compensated; also, what were the connections of the stabilizing transformer referred to in the Appendix? My experience with uncompensated machines has shown that a sudden short-circuit leads to uncontrollable transients.

I think that the author has laid too little emphasis on the simplicity and flexibility of the constant-current system as applied to certain classes of marine work.

With multiple-engined twin-screw or twin-paddled Diesel-electric vessels the constant-current system eliminates motor-operated rheostats and allows of direct bridge control without any precautions against possible misuse. Furthermore, the propulsion motors can be given any desired characteristic, such as constant power over 25% speed range changing to constant torque at lower speeds, i.e. a characteristic suitable for a tug.

* MACFARLANE, J. C., MACFARLANE, J. W., and MACFARLANE, W. I.: Paper No. 1205 U, January, 1952 (see 99, Part II, p. 421).

Another feature is the possibility of including deck machinery in the same circuit as propulsion motors with the equivalent of Ward Leonard control of all machines. Fig. C shows all the essentials of such a circuit for a Diesel-electric dredger, equipped with two 840 h.p. 126 r.p.m. propulsion motors. Each crane is motored by 62 h.p. and 25 h.p. motors, and the winches by 50 h.p. motors; the circulating current is 750 amp.

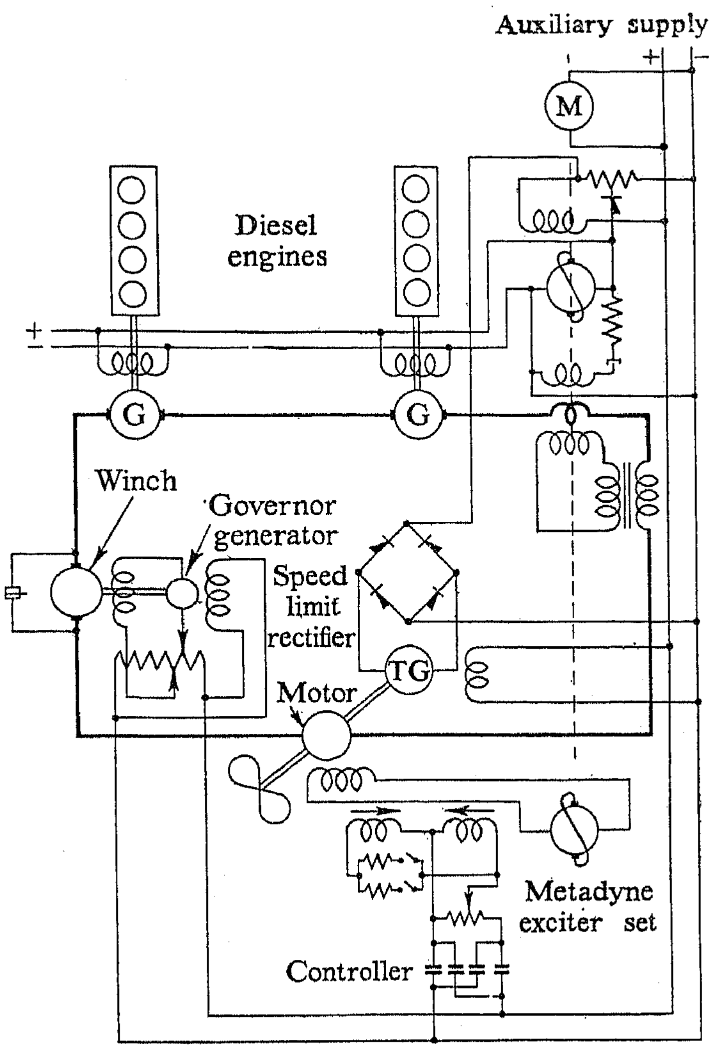

Fig. C

Mr. C. F. Tyrrell: I should like to ask the authors some down-to-earth questions concerning the user and application aspect, and confined to a.c. generators. For instance, what is actually gained by Magnicon excitation?

It appears from the paper that the Magnicon does not require an external constant-voltage reference. Is this correct?

In Section 4.6.2 a machine is described having an output average, in ratios 2 : 1. These ratios appear to be realizable without altering armature connections. How is this accomplished?

Finally, I should like to raise the question of the short-circuit characteristics of an a.c. generator with Magnicon excitation, since it affects the calculation of fault-power feeding into a network. It may be that the present output range of the Magnicon is rather too small for this question to be important at the moment, but I should like to have the authors' comments.

Mr. J. S. Michael: In Section 2.1, dealing with the advantages of separate excitation, it is stated that, since the main generator has compensating coils (allowing use of small air-gap and large electric/magnetic loading) this results in small field m.m.f.'s and magnetic fluxes and consequently small time-constants. For any voltage output the main flux should remain the same, but is it not more correct to say that the field time-constant is *increased* owing to the small air-gaps?

Also in Section 2.2.1, on design proportions, it is said that for the generator field inductance to be small, the field flux mus be small. I think that this statement should be modified, since the field inductance is proportional to the magnetic flux per unit current, i.e. effectively the slope of the generator saturation curve at any point, so that over the straight portion of the saturation curve the field inductance has a maximum value, and as saturation of the iron circuit takes place the field inductance decreases to a minimum.

In the case of a compensated generator with a small air-gap, the field m.m.f. is small, which should lead to increased field inductance as compared with a machine with a larger air-gap.

In fact the performance of the main generator is limited by two opposing factors:

(*a*) Small air-gaps which give higher values of field inductance but a minimum value of field m.m.f., for full-load operation, giving rise to a maximum forcing ratio from the exciter.
(*b*) Large air-gaps which reduce the field inductance but increase the net field m.m.f., giving a smaller forcing ratio from the exciter.

The actual design used will be a compromise taking account of any other features that may be required.

In Section 2.2.2, it is stated that by over-compensating and diverting with a non-inductive resistance, the short-circuit current can be reduced considerably. While I agree that, owing to the shunting of current, the main field is temporarily weakened, would not the reduction be caused also by the existence of a closed circuit around the compensation or interpole winding, thereby acting as a damping turn and reducing the build-up of the current peaks? Even on a non-compensated generator, heavy current peaks would tend to reduce the effective field, although possibly not to the same extent as with a compensated machine with a small air-gap. Will a diverter across the interpoles have the same effect in this case? Does it come down to the fact that a damping turn has greater effect than field weakening?

Mr. J. Hindmarsh (*communicated*): The authors have some very interesting and useful remarks to make about the Kramer generator, but in Section 2.2.2 they appear to argue that, because of the relatively unsaturated leakage paths in the compensated generator, the leakage inductance is high and the transient discharge-current consequently low. This argument seems to ignore the more important factor of mutual inductance between armature and compensating windings, which reduces the effective inductance to about 50% of that of the non-compensated machine. Certainly it is well known that, in general, a compensated generator has a much greater rate of rise, and peak current of the order of twice that for an uncompensated generator.

A further point to note is that the armature circuit time-constant is much less than the field-circuit or main-flux time-constant, and consequently the armature current will have risen considerably before it exerts any appreciable demagnetizing effect. Diverting the interpoles and compensating windings would not therefore appear to offer much diminution of the initial transient. This applies to conventional machines anyway, although on the Magnicon or metadyne types of generator, compensator diversion will be much more effective because the control-field circuit time-constant is, in fact, relatively lower and the machine therefore more sensitive to armature demagnetizing effects—which, incidentally, are in direct opposition and not just due to distortion.

However, since the oscillograms in Fig. 4 appear to be actual test results, the reason for the low transient currents must be sought elsewhere. The only possibilities seem to be:

(*a*) Some feature of the Austin circuit itself, possibly not shown in Fig. 3; e.g. additional inductance in the circuit.
(*b*) An extremely high ratio of armature to field m.m.f. with very small air-gaps and large inherent regulation.
(*c*) A much reduced field-circuit time-constant consequent upon a large-diameter machine.

It seems difficult to believe that even these considerations would be sufficient to reduce the inherent transient discharge-current of a normal compensated machine from twenty times to twice full-load current as in Fig. 4. In any event, the application would seem to be restricted to machines of low rating, since commutation considerations would otherwise preclude the use of very small air-gaps, non-inductive interpole diverters and brushes running out of neutral. Further, the expense of using large-diameter machines would seem to make a constant-current system using uncompensated generators in conjunction with Magnicon or metadyne exciters a more economical proposition.

Dr. E. Rosenberg (*Colombia: communicated*): Although Maj.-Gen. Tope and Mr. Price mentioned in the London discussion the Rosenberg dynamo and the original patent specification of 1904, I am not sure whether they and the experts in general are aware of Mr. J. L. Woodbridge's application of the cross-field generator (Rosenberg dynamo) in the constant-voltage train-lighting system of an American organization; a report of this has been published.*

In Fig. D a simplified diagram† of connections is given with

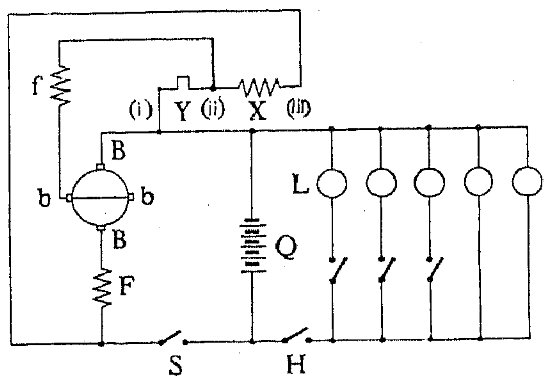

Fig. D.—Simplified Woodbridge–Hull diagram of connections.

a modification suggested by R. C. Hull; it is a little clearer than the original diagram.

Q represents the battery of 16 cells, which Woodbridge used, L the lamps, S the well-known automatic switch which, when starting the train, connects the dynamo as soon as the proper voltage is obtained and disconnects it when, in stopping the train, reverse current occurs. H is a hand-operated switch. BB are the main brushes, bb the short-circuited auxiliary brushes of the Rosenberg dynamo, F the series exciting coil (compensating coil), and *f* a very thin wire controlling coil of the field, connected between the auxiliary brushes bb and point (ii) of a small auxiliary circuit (i), (ii), (iii) consisting of an iron wire Y in a hydrogen-filled bulb and an ordinary resistor X, which are series-connected across the full dynamo voltage. In the state of dull incandescence the resistance of the iron wire rises considerably with an increase in temperature while X practically maintains constant resistance.

With a definite dynamo voltage the current flowing through the circuit (i), (ii), (iii) will be such that (ii) has the same potential as the auxiliary brushes bb, and no current will flow through the controlling coil f. In starting the train, while the voltage is lower, the resistance of the iron wire Y is reduced and a positive current flows through the controlling coil f. When the dynamo voltage is even very little increased over the critical value, the current through the controlling coil is reversed. I mentioned in an Institution paper* under the heading "open-circuit voltage," that the residual magnetism may vary from 1 to 3% of the full field. Such an amount, if not counteracted, could cause excessive current in a train lighter at high speeds.

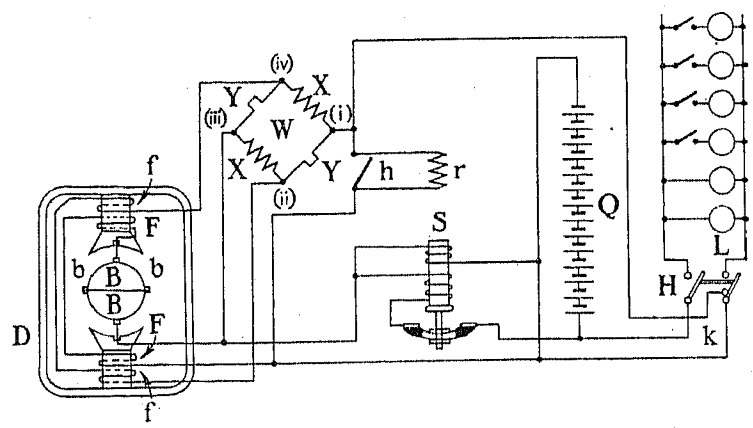

Fig. E.—Original Woodbridge diagram of connections.

In his original diagram of connections, identical with Fig. E, Woodbridge connected the controlling field coil (f) between the points (ii) and (iv) of a Wheatstone bridge, and also provided in series with the bridge an additional resistor (r), normally shirt-circuited by the switch (h), which would make it possible to overcharge the battery in day-time. However, when the double-pole lamp switch H is in the closed position, the resistor r is short-circuited by auxiliary contacts. According to the report in *Electrical World*, during 12 months of service and 150 000 miles of travel, the overcharging was never required.

Fig. F shows the machine voltage/speed curve, and it appears that from 600 to 2 200 r.p.m. (and naturally also at higher speed) the voltage is kept constant at 36 volts.

* *Electrical World*, 1913, 62, p. 916.
† ROSENBERG, E.: "The Direct-Current Cross-Field Machine" (Springer, Berlin, 1928), Fig. E.

* ROSENBERG, E.: "Rosenberg Dynamo with Fixed Polarity," *Journal I.E.E.*, 1939, 85, p. 423.

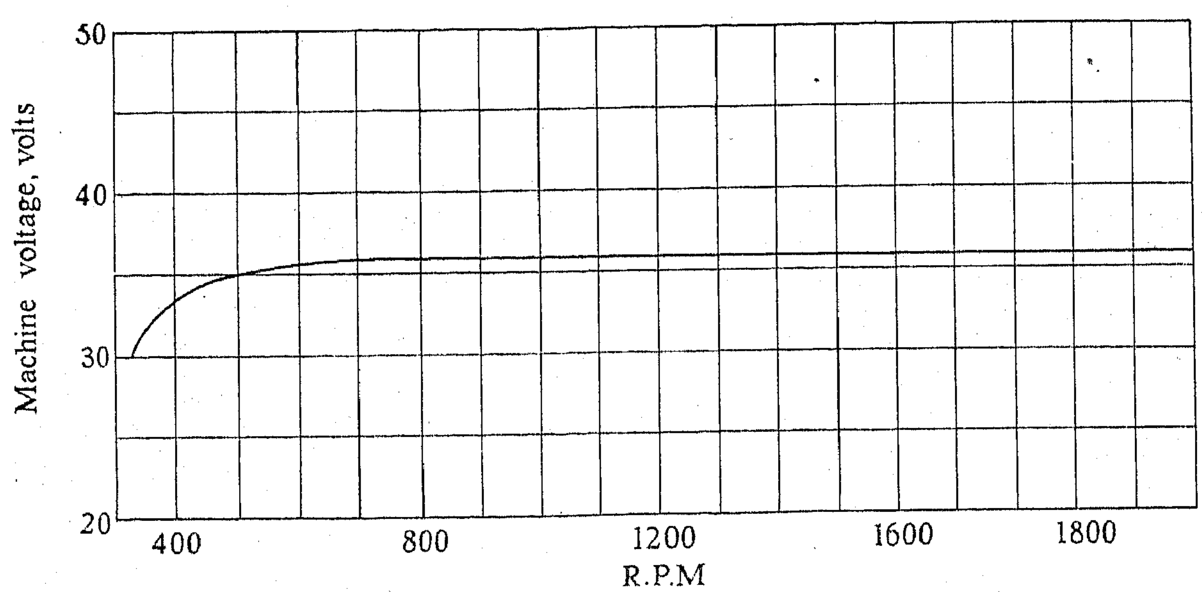

Fig. F.—Dynamo voltage/speed curve.

No exact data are given about the input of the controlling coil, but I have no doubt that for a constant-speed generator it could be kept within a small fraction of a watt.

I do not know whether Mr. Price had the Woodbridge arrangement in mind when he said, "I believe that a modified and compensated Rosenberg generator has been employed in connection with battery charging, but unfortunately the control field was applied among the main flux axis and therefore just failed to anticipate the amplidyne." In my opinion the compensation of the secondary armature field (with the axis of the auxiliary brushes bb) has practically nothing to do with the characteristic of the amplidyne. In a book* referring to Woodbridge, Pestarini's metadyne and two proprietary amplifiers, I did not hesitate to say that Alexanderson, Edwards and Bowman, of an American organization, used the Rosenberg dynamo as amplifier. I believe this statement to be correct, although it is not meant in any way to detract from the high merits of the inventors of the amplidyne who opened to the generator a field of application of which neither I nor, I imagine, Woodbridge ever thought, and which has proved so fruitful to industry.

Among the many important applications of the constant-current system described by the authors, the most remarkable appears to be the equipment for sugar drying (Section 2.5.4). It is a bold idea to use d.c. motors in series to drive centrifugal machines for hydro-extraction in order to recover the stored energy of one machine for starting another. It would be interesting to know whether the starting and stopping is done by a hand-manipulated diverter to the exciting coil or whether a scheme of special exciters has been used. Also data as to output and speed of the motors, and a statement as to the way in which the motor armature is mechanically connected to the centrifugal drum, would be interesting and help one to appreciate the commutating difficulties—which seem to have been overcome so well, considering that the scheme has successfully been in service more than eight years.

[The authors' reply to the above discussion will be found on page 401.]

DISCUSSION BEFORE A JOINT MEETING OF THE INSTITUTION AND THE INSTITUTION OF ENGINEERS, AUSTRALIA, AT MELBOURNE, 10TH SEPTEMBER, 1952

Mr. H. E. Westgarth: It appears that the Magnicon would have applications for large alternator voltage-regulation if it could be constructed in larger sizes. With the present trend towards a high rate of response for machine-excitation systems to assist in maintaining system stability, particularly where systems include hydro-electric stations with long transmission lines, it seems that a voltage-regulator system employing a Magnicon directly connected to the alternator field would provide the high rate of response, with no need for devices to prevent hunting or instability in the voltage-regulating system.

It does seem very significant, however, that the only applications of the Magnicon as an alternator voltage-regulator mentioned by the authors relate to relatively small machines having excitation requirements far below those of conventional power-system alternators.

Mr. D. Broadbent: It is proposed to show that the system shown in Fig. 3 of the paper with certain circuit parameters given in Section 9.1.2 is not an unstable system as the authors suggest. This may be seen if the equations of Section 9.1.1 are rewritten in the form

$$(a_0D^3 + a_1D^2 + a_2D + a_3)\, i = (b_0D^2 + b_1D + b_2)e_1 \quad . \text{(A)}$$

Then, on substitution of the circuit parameters for the least stable case, Routh's criterion may be applied:

$a_0 = 3{\cdot}465 \times 10^{-8}, a_1 = 10{\cdot}235 \times 10^{-6}, a_2 = 188{\cdot}6 \times 10^{-6}$, $a_3 = 0{\cdot}012\,22$, all being positive.

Also $(a_1a_2 - a_0a_3) = 1{\cdot}93 \times 10^{-9} - 0{\cdot}423 \times 10^{-9}$ is positive, which indicates that the system is stable.

Alternatively the system may be analysed as a servo mechanism.

In Fig. G, no instability can take place in the link between e_2 and e, there being no feedback in that circuit, and they will therefore be eliminated from the servo diagram. Instability is possible, however, between the m.m.f. $(i_1 - i)$ and the output current i, and so the loop will be built up around these quantities.

By substitution eqn. (2) may be rewritten

$$(i_1 - i) = \frac{e_1}{r_1 + L_1D} - \frac{1 + \dfrac{L_1 - M}{r_1}D}{1 + \dfrac{L_1}{r_1}D}\, i = F_1(D)e_1 - F_3(D)i \quad \text{(B)}$$

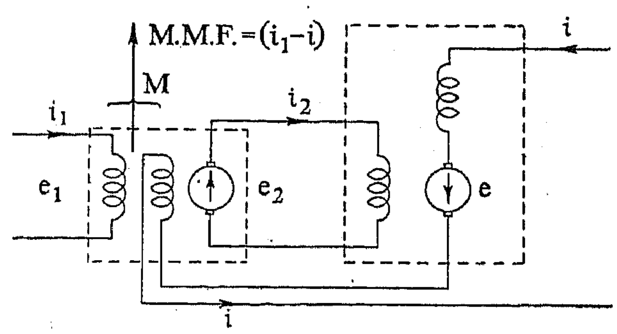

Fig. G

The m.m.f. has been split up into a part depending on e_1 (which becomes a constant if $e_1 = E_1$ = constant) and a part depending on i.

Further, from eqns. (1) and (3),

$$\frac{i}{i_1 - i} = \frac{\left(\dfrac{ML_2}{K_1K_2}D^2 + \dfrac{Mr_2}{K_1K_2}D + 1\right)}{\left(1 + \dfrac{L - M}{r}D\right)\left(1 + \dfrac{L_2}{r_2}D\right)}\frac{K_1K_2}{rr_2} = F_2(D) \quad \text{(C)}$$

The equivalent circuit is shown in Fig. H.

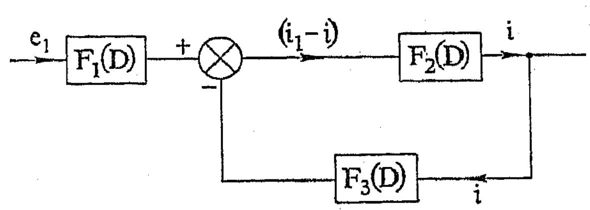

Fig. H

To examine the loop for stability we make the input constant (by putting $e_1 = E_1$) and break the loop as shown in Fig. J. A sinusoidal signal x at frequency ω is inserted at point X, and the resulting signal y appearing at Y is observed, together with its phase and magnitude compared with the signal at X. This magnitude and phase difference will vary as ω is varied.

The series transfer function round the loop given by

$$F(D) = F_2(D)\, F_3(D) \quad . \quad . \quad . \quad . \quad . \quad \text{(D)}$$

If the frequency ω at which y is 180° out of phase with x

* Rosenberg, E.: "Der Werdegang eines Ingenieurs" (Springer-Verlag, Vienna, 1950).

*

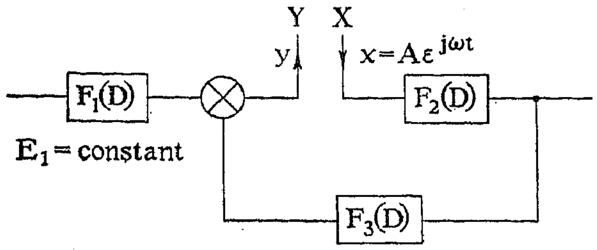

Fig. J

corresponds to $y/x = 1$, i.e. to positive feedback, the system is unstable and will oscillate at that frequency. If $y/x > 1$ the oscillations will build up until limited by circuit non-linearities.

When x and y are sinusoidal signals of frequency ω it is

Finally if we put $u = 0{\cdot}00303\omega$

$$KG(ju) = \frac{16[(ju)^2 + 0{\cdot}0161ju + 1]}{(1 + 1{\cdot}21ju)(1 + 62ju)(1 + 23{\cdot}1ju)} \quad \text{[D(iii)]}$$

If we adopt usual practice and express the magnitude of $KG(ju)$ in decibels, thus:

$$\begin{aligned}|KG(ju)|_{dB} &= 20\log_{10}16 + 20\log_{10}|[1 + (ju)^2 + j0{\cdot}016u]| \\ &\quad - 20\log_{10}|(1 + j1{\cdot}21u)| - 20\log_{10}|(1 + j62u)| \\ &\quad - 20\log_{10}|(1 + j23{\cdot}1u)| \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{[D(iv)]}\end{aligned}$$

each part may be plotted against log u and summed to give $|KG(ju)|_{dB}$ against log u.

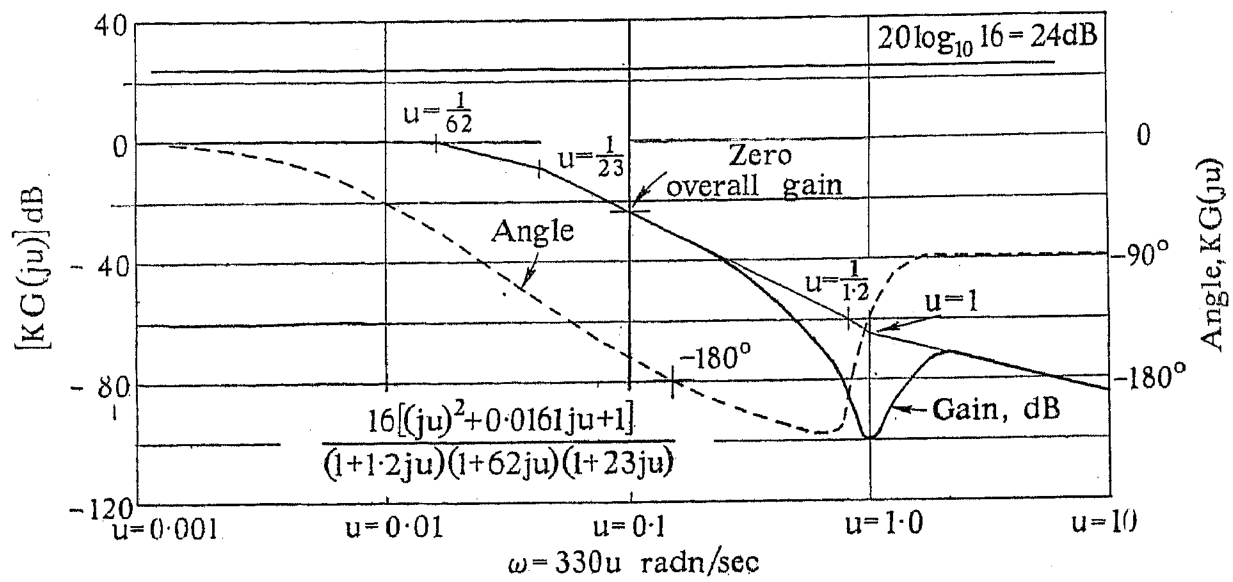

Fig. K

justifiable mathematically to rewrite eqn. (D) as shown in eqn. (D'):

$$y = x[K_2G_2(j\omega)][K_3G_3(j\omega)]$$

Now $\qquad F(D) = F_2(D) \times F_3(D) \qquad$ (D)

$$= \frac{K_1K_2}{rr_2}\,\frac{\left[\left(\frac{ML_2}{K_1K_2}D^2 + \frac{Mr_2}{K_1K_2}D + 1\right)\right]\left(1 + \frac{L_1 - M}{r_1}D\right)}{\left(1 + \frac{L - M}{r}D\right)\left(1 + \frac{L_2}{r_2}D\right)\left(1 + \frac{L_1}{r_1}D\right)}$$

Substituting the actual values given in the Appendix (as above)

$$F(D) = \frac{16[(0{\cdot}00303D)^2 + 0{\cdot}0000487D + 1](1 + 0D)}{(1 + 0{\cdot}00367D)(1 + 0{\cdot}188D)(1 + 0{\cdot}07D)} \quad . \quad . \quad . \quad . \quad \text{[D(i)]}$$

$$KG(j\omega) = \frac{16[(0{\cdot}00303j\omega)^2 + 0{\cdot}0000487j\omega + 1]}{(1 + 0{\cdot}00367j\omega)(1 + 0{\cdot}188j\omega)(1 + 0{\cdot}07j\omega)} \quad . \quad . \quad . \quad . \quad \text{[D(ii)]}$$

The phase shift due to each part may be plotted and summed to give

$$\underline{/KG(ju)} = 0 + \arctan\frac{0{\cdot}0161u}{1 - u^2} - \arctan 1{\cdot}21u - \arctan 62u - \arctan 23{\cdot}1u \quad . \quad \text{[D(v)]}$$

Fig. K shows the summation of magnitudes and phase angles to give $KG(ju)$.

It will be seen that at no value of u (and therefore ω) is there a positive gain associated with a phase shift of $-180°$, and the system is therefore stable.

If the system were unstable it would be possible to say which of those parts would have to be modified, and by how much, to make the system stable. As it is we could say which of the parts need to be modified to make the system unstable.

There is also an obvious irregularity in Section 9.1.2 in the solution for i_1, when $M = -0{\cdot}0007H$. The power of ε is written as $18{\cdot}5t$ in the second term of the solution and $-18{\cdot}5t$ in the third term.

[The authors' reply to the above discussion will be found on page 401.]

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, AT BIRMINGHAM, 13TH OCTOBER, 1952

Mr. J. G. Henderson: The description and dynamical analysis of machines with feedback can be greatly facilitated by the use of dependence diagrams,* which show the sequential relationship between quantities; e.g. the relationship between m.m.f. and flux, flux and e.m.f. and so on throughout the machine, which ultimately indicates the closed-sequence nature of a part of even the whole of a machine sequence. Where these relationships are non-linear they can be sketched on the diagrams and there assist in the determination of the steady-state response of the system.

When used for alternator voltage-control the Magnicon of Fig. 6 is stated to be slightly over-compensated. This constitutes a system with positive feedback on the control axis and a positive

* TUSTIN, A.: "D.C. Machines for Control Systems."

mutual inductance between the compensating winding and the control winding, the latter being a stabilizing feedback during transients. The former, however, has an anti-stabilizing effect. Is the degree of positive feedback insufficient to cause self-excitation of the Magnicon or does the stability of the closed loop depend on overall feedback?

In Section 4.1.2, it should be emphasized that the comparison is between an alternator without an automatic voltage regulator and one with a Magnicon exciter. I think one would expect a similar saving in field copper in an alternator designed for use with an automatic voltage regulator, although to achieve the same speed of response a high-ceiling-voltage exciter would be needed. The Magnicon system of excitation is certainly a robust alternative to control by an automatic voltage regulator, but what is the relative cost?

Referring to Table 3, I should like to have seen the basis of the comparison stated more fully.

Prof. A. Tustin: The machines described in the paper belong to the extensive class of generators in which approximate constancy of current is obtained by the use of feedback. It is often forgotten how early this principle appeared in the history of the development of electrical machines: there is for example a British Patent to a French inventor, A. I. Gravier (British Patent 1211), dated 1882, that clearly describes the principle of the cross-field constant-current generator, referring to a Gramme-ring armature. This was the ancestor of the authors' Magnicon as well as of the Rosenberg generator, the metadyne and the amplidyne. In the early years of this century there was active exploration of the problem of obtaining constant or regulated current output because of its interest for battery charging and for arc lighting. Papers by Rosenberg (1905), Osnos (1907) and others anticipated very many of the arrangements that have been incorporated in modern machines. There has, however, been a change of emphasis in the discussion of such machines resulting from their growing use as power amplifiers in control systems. This puts the emphasis on their dynamic as distinct from their static characteristics, and the appropriate analysis was found ready to hand in the theory of feedback amplifiers developed by Nyquist and others in the 1930's.

The most important peculiarity of a d.c. generator as a power amplifier is that the exciting winding is inductive, and in a simple separately-excited generator the time-constant of the field winding is easily shown to be proportional to the power amplification at any point on the straight part of the characteristic, the constant of proportionality being $A_f/A_s v_p$, where A_f is the m.m.f. of the field, A_s the ampere-stream of the armature, and v_p the peripheral speed. For usual values of these quantities the time-constant is about $0 \cdot 001$ sec for each unit of P, the power amplification. For example, if the power amplification is 1 000, a field-winding time-constant of about 1 sec would be a usual value. The designer's primary aim in machines for use in control systems should therefore be to reduce the value of $A_f/A_s v_p$, and many of the authors' recommendations, advocated as a result of experience or of independent arguments, will be seen to be consistent with this observation.

Mr. F. Brassington: Is it not possible that the Magnicon can be regarded as a unit consisting of two conventional exciters? By putting two such exciters in cascade the same effect as produced by a Magnicon might be obtained.

Mr. V. Easton: The use of the words "truly compensated" in Section 4 in the description of the Magnicon-excited alternator is to be deprecated since it suggests that the armature reaction is completely neutralized by windings, the m.m.f. of which may be varied in both magnitude and phase. Actually, it is no more than opposed by additional current in the single field winding, the amount of the extra excitation being determined from the effect of the armature reaction on the terminal voltage. In this respect, it differs in no way from a conventional alternator of either the salient-pole or the cylindrical-rotor type, controlled by a voltage regulator, both types having proved satisfactory over many years, at least in the larger sizes. The performance of the alternator then depends largely on that of the automatic voltage regulator, and the permissible modifications to its design constants should be considered primarily from the point of view of the reliance which can be placed on the voltage control means rather than from any inherent characteristics of the alternator alone. The outstanding feature of the Magnicon exciter, I believe, is the neat manner in which a voltage comparator, an amplifying dynamo and the exciter have been combined in a single robust machine, the resulting degree of reliability being higher than that of a separate voltage regulator and exciter for a small machine, so permitting a greater reduction in the alternator size.

It is unfortunate that the authors, when discussing relative alternator designs, have departed from a well-known and clearly defined standard of comparison, namely the short-circuit ratio, and introduced the ratio (field m.m.f.)/(armature m.m.f.), as various interpretations may be placed on the latter.

On the basis of no-load/full-load field m.m.f. of $0 \cdot 5$ from Fig. 11, and the ratio (field m.m.f.)/(armature m.m.f.) of $3 \cdot 2$, it appears that the short-circuit ratio is of the order of $0 \cdot 75$ for a small machine. To clarify the position, would the authors please quote values of short-circuit ratio (*a*) for a normal Magnicon excited alternator, (*b*) the minimum value for an alternator operating at minimum voltage with a 10/1 voltage range as in Fig. 10, and (*c*) the value for the adjustable-voltage-level machine mentioned in Section 4.6.2 for full output at 50% voltage.

Mr. J. P. Huggard: It would be an advantage if the authors would give a comparison of the size and weight of a Magnicon-type exciter with a standard exciter for an alternator for use with, say, a carbon-pile automatic voltage regulator, assuming both machines have the same output and speed. Is there any difficulty in providing Magnicon exciters for large alternators, or is it preferable to use them as pilot exciters in conjunction with main exciters? I presume that for larger outputs it would be necessary to provide the Magnicon exciters with four compoles and two sets of commutating pole coils, one set in series with the short-circuited brushes, and the other in series with the output brushes.

There is no mention in the paper of anti-hunting coils being used on the Magnicon exciter. Is there any particular reason for this? Most forms of amplifying exciter require some anti-hunting feature. Is its absence due to the fact that the overall voltage amplification of the Magnicon exciter is not high and it is used with a small alternator with a comparatively small time-constant?

The use of a distributed field winding for the alternator, instead of the usual salient-pole construction, is of doubtful value, its main advantage apparently being that it has a lower time-constant. The lower time-constant is due mainly to the fact that it has a larger mean length of turn, and for a given m.m.f, it has a higher copper loss than the salient-pole type of coil. It appears that it would be preferable to use the salient-pole construction with its lower copper loss, and improve the time-constant by means of an external resistance, thus giving a smaller and more efficient machine.

What is the effect, on the overall accuracy of the voltage control of the Magnicon-excited alternator, of variation in the brush contact of the short-circuited brushes?

In connection with the 160 kW constant-current generator referred to in Section 2.3, does the statement mean that the

voltage of the 160 kW generator was reduced from the full-load value to zero in 1/25 sec? Do the oscillograms shown in Fig. 4 refer to the 160 kW generator, and is it possible for a time scale to be given?

Mr. K. Wilcox: How stable is the reference point in particular, in the circuit used for automatic voltage regulation? The authors state that saturation comes into the picture, and it is a fact that iron is not entirely stable at its saturation point, since it varies slightly with ambient temperature and self-heat.

We know that Magnicon-excited alternators are manufactured to give a regulation of $\pm 1\%$, and this represents a small proportion of the total feedback. What is the extent of self-heat and ambient-temperature errors?

The control circuit comprises a resistance-fed full-wave rectifier, shown coupled between the red phase and the neutral of the output. If the feedback were taken from two phases would not a better performance be expected on unbalanced loads?

The authors claim that the negative-resistance characteristic of the rectifier plays a part in compensation of error, but surely this effect is largely swamped by the comparatively large value of series resistance necessary to reduce the self-heat in the copper windings to acceptable proportions.

Since the output from the network is rectified it will be proportional to the average value of the output voltage and not the r.m.s. value. Would not this cause errors if harmonics were present in the output waveform?

Mr. G. Whiteside: I am not quite clear how temperature affects the control (Section 4.4.1), in view of the use of rectifiers. How is temperature compensation introduced?

Mr. A. J. Mare: Section 4.2.2 does not seem to me to give any information on the subject of running a Magnicon-type alternator in parallel with more than one set with conventional automatic regulation and the conventional load-sharing devices incorporated in the automatic regulators. What does one do if one wants to add a Magnicon alternator and run it in parallel with two other sets with conventional load-sharing automatic voltage-regulators?

Dr. W. G. Thompson: It follows from fundamental considerations of rotating machines that the torque is proportional to the flux per pole and the armature current, while armature e.m.f. is proportional to the product of the flux per pole and the speed, so that any change in the excitation of the machine must give rise to a change in torque and speed—which proves particularly effective as a method of control on the so-called constant-current system, for the precision needed in dealing with large masses in connection with winching, hoisting, etc.

The authors refer to the oscillation which may occur in the systems of control they describe, and I should like to ask to what extent the mechanical properties of the machines come into this question. Is it that the period of oscillation is so high that the machines continue to run at some mean speed, and if so between what parts of the system does the energy transfer take place?

Fig. 4 shows the conditions which may result, but it would be very valuable if we had an indication of the time scale on the oscillogram in Fig. 4 to show whether the oscillations were slow or fairly rapid.

Mr. P. Scott: Against "Maintained Oscillations" in Table 3 the authors state that these are not possible with the Magnicon exciter system. It seems to me that the Magnicon exciter plus its alternator or generator has at least three time-delays and sustained oscillation is therefore possible if the amplification is high enough. Would the authors confirm that that is the case?

[The authors' reply to the above discussion will be found on page 401.]

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 17TH NOVEMBER, 1952

Mr. J. O. Knowles: I note in the paper a reference to a 160 kW 250 amp 640 volt constant-current generator for winch control as a standardized size: the control-gear maker usually sees the motor maker as one who must carry far more standard sizes in his range than the control-gear maker. The constant-current system does seem particularly suitable for winches—the torque at standstill having the same steady strong slow draw-bar pull that a steam engine has. Winch control is a problem for conventional supplies—particularly a.c. supplies. That alternating current has made more headway in all countries on tankers illustrates this point, since a tanker's cargo presents no problem in lifting by means of alternating current. As the constant-current system has been established for years and a.c. winch control is still in the development stage, what has kept the constant-current system from more general use?

Now, as to constant voltage and constant frequency, recent investigation in this area shows that the maximum rate of change of frequency recorded has been about 0·1 c/s. The mains frequency has at least been more consistent than the mains voltage. For research and testing we can often put up with a slow change in frequency, but rapid variations in voltage are much more troublesome. We should like a steady reference voltage, correct not to 10% but to 0·1%, and a waveshape without change in its harmonics, even if some small harmonics are present. Can the authors offer us such a supply—with a disturbance time of, say, 5 cycles on 50% change in load?

The paper refers to marine, military and welding applications. Have the authors anything interesting to offer for Ward Leonard and other industrial applications, such as reversing drives?

Mr. B. Skenfield: I feel that it is worth while pointing out that the straightforward drooping-characteristic 3-winding generator giving a short-circuit current controlled by the separately excited field is still the ideal machine for many purposes. As the authors state, a generator having an inherent constant-current characteristic may be a dangerous thing to short-circuit, but in many applications of 3-winding generators the possibility of this does not arise. In Ward Leonard control as applied to excavators, for example, each motion has its own 3-winding generator and separately-excited motor, the control being mainly on the separately-excited field of the generator. By suitable design—briefly by making the self-field resistance line parallel to the initial straight part of the generator magnetization curve—the current for the slew motion can be kept substantially constant at a predetermined value during the accelerating period, even though the static voltage/current characteristic may be fairly well removed from the constant-current characteristic. There are thousands of 3-winding generators of more or less conventional design in use or being manufactured, and it is an interesting point that in the latest excavators being developed in this country and America for bucket sizes up to and including $3\frac{1}{2}$ yd^3 3-winding machines will continue to be used. In these equipments the hoist generator has a short-circuit current of about 1 000 amp and an open-circuit voltage of 580 volts. For larger equipments amplidyne control has been successfully used and is preferable in view of the high current and time-constant of the generator fields.

As to the Magnicon, it is always a matter of interest to designers of conventional d.c. machines that armature reaction, which normally imposes so many design limits, is put to good use in amplifying exciters, although even so, the armature

reaction on the control axis is objectionable and must be neutralized by a compensating winding. Some speakers in the discussion before the Utilization Section mentioned the Rosenberg machine, and a paper read before the American I.E.E. in 1918 described a constant-voltage generator having a 2-pole armature in a field system having four polar projections. It may seem surprising that such a long time elapsed between those early developments and the production of modern amplifying exciters, but as with many similar inventions, the machines were developed when the need for them became imperative.

Considerable emphasis is laid on the fact that these machines have a high rate of response. There are, however, many applications where a response time of say 0·05 sec is quite unnecessary, even though the amplifying properties are required. Have the authors ever tried a salient-pole system having a non-laminated yoke, thus obtaining a much cheaper machine? Work recently carried out in the organization with which I am associated, using conventional d.c. generators under high degrees of field forcing and also under sinusoidal excitation, suggests that a solid yoke introduces considerably less delay than popular belief and classical theory lead one to suppose, and while laminated construction is of course essential for ease of manufacture for a distributed compensating winding and field, one would imagine that the trapezoidal waveform of armature m.m.f. in the Magnicon would enable normal d.c. machine construction to be used, with low cost and results adequate for many purposes.

Mr. J. E. Macfarlane: A number of years ago a cross-field machine was tried for the low-voltage supply on traction equipment, but finally I believe an automatic voltage regulator was used. Can the authors say when it is worth while changing from such a regulator to a Magnicon exciter? A further reference* to 3-winding generators may interest the authors. The comparison of motors at 1 000 r.p.m. in Table 1 is misleading since it is only an indication of frame sizes, and for the diversity factor the figure is about 4 instead of the 7·7 stated. The authors mention very short air-gaps, and I wonder whether harmonic troubles were experienced, since we have found pronounced slot-ripples in a 15 kVA alternator at the college which has a slot opening of 3 mm and an air-gap of 2·75 mm at the pole centre. A film strip shows what occurs. The authors are somewhat pessimistic giving a voltage regulation of 30% with a short-circuit ratio of 3 : 1. On the alternator referred to the voltage regulation is $11\frac{3}{4}$% at 0·8 power factor lagging, the short-circuit ratio being 3 : 1. Reference might also be made to a paper by C. W. H. Minchin, in which he describes an interesting self-contained machine.†

Dr. David Morris: It is possible to over-emphasize the importance of speed of response when considering the stability of automatic control systems. Multi-stage amplifiers are sometimes misleadingly described as having a high speed of response, whereas the significant fact is that the amplification is high enough to afford scope for shaping the response by means of feedback. The excitation energy in individual stages does of course limit what can be done by means of feedback, and here again it is misleading to describe the stages in terms of time-constants, which make a virtue out of resistance. If resistance is used for the purpose of stabilization, the designer should be fully conscious that he is so doing. To ensure this, when investigating the fundamental limitations imposed by energy storage, it is sometimes profitable to consider how the circuits would be arranged if a material of infinite conductivity were available for winding the machines.

The authors have shown that by using a suitably distributed field winding in alternators, the resultant m.m.f. becomes the difference of two (almost) sinusoidal m.m.f.'s, which favours the production of a sinusoidal working flux. Another real advantage is that the air-gap can be reduced to the mechanical limit over the whole of the pole-face, thus reducing the excitation energy to a minimum.

At the end of Section 2.2.2, the term "brush lead" appears to mean displacement in the direction of rotation, whereas in Fig. 4(*b*) it appears to mean displacement against rotation. In the same Section it is stated that the expedients adopted "demagnetize the main field if the current tends transiently to rise." This is true for the use of a diverting resistor across compensator or interpole. With regard to brush-shift, I agree that this will produce a decompounding effect that will tend to stabilize the system, but it appears to me that the coupling which is introduced between the armature and field circuits, both directly and via the commutating turns, will make the decompounding less under transient than under steady-state conditions. I should be glad if the authors would clarify their use of the word "transiently" in this respect.

The reading of Section 3.2.3 would be facilitated by the publication of a diagram of the saturable-pole arrangement, as shown during the presentation of the paper. In Section 3.2.1, two control coils and two compensator coils are mentioned. The function of the two control coils is explained in Section 3.2.3, but clarification would be welcomed for the statement that there are two compensator coils.

There appears to have been some inaccuracy in the transcription of Section 9.1.2 from the original calculations. In my view, a system having the equations and parameters quoted would be stable for all values of mutual inductance algebraically greater than about $-0 \cdot 8$ mH. Furthermore, the results quoted show several inconsistencies for the final steady-state conditions.

I was not aware of the terms "Austin" and "Kramer" as applied to the generator systems described, and I think that the paper would be improved from an educational point of view if references could be given to the literature in which these terms were first used. Within the confines of the paper, the authors have been able to indicate the interesting techniques associated with the utilization of motors on constant-current systems, and references to publications giving fuller details would be valuable.

Mr. A. S. Aldred: I believe it is a fact that the machines which have come to the fore in recent years for use in control systems, namely the amplidyne, the metadyne and the authors' machine, the Magnicon, are all generators. These generators work on the principle of cross-fields. Would it be possible to develop a motor, working on the cross-field principle, whose speed could be made proportional to a voltage applied to a control winding? If this were possible, systems requiring three machines for control purposes, for example the Ward Leonard and series-booster systems, could be replaced by one machine. Can the authors say if any work is intended on motors with cross-field operation?

Mr. C. V. Jones: There is one point which occurred to me when I first read the paper and although it was raised in the discussion at London I still find it misleading. The authors refer to their Magnicon-excited alternator as a "fully-compensated alternator," although they admit that compensation by means of a series winding is impossible.

At all power factors other than zero, there will always be a component of armature reaction along the quadrature axis of the field system, and true compensation of this component could be accomplished only by a subsidiary winding on this quadrature axis, if indeed it could be done at all. The authors' method of replacing a salient-pole by a cylindrical-rotor alternator will, by introducing a low-reluctance quadrature magnetic path, actually accentuate the effect of armature reactions in this axis.

* TOWLE, E. L. N.: "Some Aspects of Diesel-Electric Marine Propulsion," *Liverpool Engineering Society Bulletin*, December, 1950.
† MINCHIN, C. W. H.: "A Self-Excited Compensated Alternator," *Journal I.E.E.*, 1946, 93, Part II, p. 373.

Would the authors agree that the originality of their alternator lies not in the alternator itself, but in the method of excitation, and that it is incorrect to refer to the machine as "a fully-compensated alternator"? Alternatively, if their machine is to be regarded as compensated the same is true of any cylindrical-rotor machine.

[The authors' reply to the above discussion will be found on the next page.]

WESTERN UTILIZATION GROUP, AT BRISTOL, 24TH NOVEMBER, 1952

Mr. R. W. Maltby: Referring in particular to the Magnicon alternator, I should be pleased if the authors could indicate its scope of usefulness as a source of power controllable in voltage and frequency for use by test rooms.

It appears that normal types of voltage and frequency regulators are not sufficiently versatile to cope with the very large ranges usually expected from test supply alternators, and, in consequence, they are generally abandoned in favour of simple motor and alternator field rheostats. This results, of course, in the machines having particularly poor regulation, which becomes important with fluctuating loads. Furthermore, they are often operated with fields so weak that the machines become unstable.

I should therefore be pleased if the authors could state whether the Magnicon alternator is capable of being operated at variable voltages and frequencies and, if so, the ratios of variation permissible.

Mr. A. J. Parsons: I have had some experience with split-pole generators such as the amplidyne, and I have found that one of the obstacles in the way of obtaining very close regulation is the hysteresis of the generator field circuits. On some machines of American origin I was interested to find that, in addition to the normal field winding, a further winding having twice the number of poles of the main winding was fitted and arranged for a.c. excitation. The alternating current was obtained from a small generator winding adjacent to the main fields and excited by a permanent magnet fixed to the generator shaft. I was not able to learn how effective this was in overcoming the effects of hysteresis, and I should like to know whether the authors have found hysteresis a problem and whether they have had to adopt any special measures to reduce its effect in the Magnicon.

A further point relates to the suitability of the Magnicon alternator for supplying power to X-ray apparatus which requires close voltage regulation. This is a difficult duty, because full load can be applied to the alternator for as short a period as 0·04 sec, which is much shorter than the response time of 0·1 sec of the Magnicon alternator. Have the authors had any experience with their alternators on this type of load?

Mr. C. W. H. Minchin: The part of the paper which describes the Magnicon alternator has been especially interesting to me since the organization with which I am associated makes a machine which gives very similar results with an entirely different method of control. The control of our machine is actuated by a combination of the output current and power factor and, in view of its principle of operation, must be constructed with a revolving armature.

This type of construction is generally considered to be cheaper than the rotating-field alternator, in particular for 4-pole machines, and I am surprised, therefore, to find that the authors favour the revolving-field type.

In Section 4.1 mention is made of the small air-gaps employed. I should be pleased to know whether this has caused any excessive core loss.

I was very surprised to see in Section 4.6.2 that the copper temperature rise of a double-voltage machine increased only 12% when the copper loss was increased to 400% of its original value. I should be pleased to know whether the copper loss in this machine was any higher than usual even on the higher current rating. I should also like to know the approximate (field m.m.f.)/(armature m.m.f.) ratio when this machine was running at the lower voltage.

[The authors' reply to the above discussion will be found on the next page.]

EAST MIDLAND CENTRE, AT LOUGHBOROUGH, 20TH JANUARY, 1953

Mr. H. T. Price: The authors have traced the development of the Magnicon amplifying generator from the Kramer 3-field generator. This is most interesting because it illustrates the process of evolution in design. Each difficulty poses a problem which, when solved, leads to one further step in the evolution.

The amplidyne generator stemmed from the same source, i.e. via the Rosenberg constant-current generator and the Pestarini metadyne convertor. The amplidyne is known on the Continent as a neutralized Rosenberg generator. Dr. Rosenberg was the first to introduce the principle of armature-reaction excitation. For students of this subject, a perusal of the original Rosenberg patent dated 1904 is worth while. It will be found that he proposed two methods for the development of constant-current generators. The first method was to displace the magnetic axis of the two fields relative to each other so that, for example, in the case of the 2-pole field, they are approximately at right angles one with the other. The second method was to arrange the two fields and wind for a different number of poles so that the poles may be described as being of different pitch. The latter method is the basis of the two-stage Magnavolt or Rototrol amplifying generator, whereas the first method is the basis of the amplidyne. I should be glad if the authors would comment on the relative methods of the metadyne and Rototrol or Magnovolt-type rotating amplifiers.

Referring to Section 4.1, I fail to see how employing the distributed-field system gives a truly compensated machine. An advantage of the distributed-field rotor is that the air-gap reluctance is uniform and the resultant m.m.f.'s are not distorted by the armature-reaction quadrature-axis component, and also the lower time-constant of this type of winding.

An important factor is the rate of boost of excitation with load growth. One can only design with a small ratio of field strength to armature reaction provided that the field excitation can be boosted sufficiently rapidly to maintain stable operation.

It is my experience that direct compounding of alternators gives very rapid response, but unfortunately, except for fixed-power-factor conditions, it is difficult to obtain the excitation required for all load conditions and a degree of over-excitation normally results. I know of one system of automatic braking for induction motors which employs direct compounding. In this system, two phases of the 3-phase stator are fed through rectifiers from series current transformers in the rotor circuit and the third phase from a d.c. exciter. In this manner we have a truly compensated alternator for unity-power-factor condition, and I can assure you that a rapid response to load change results.

There is no doubt that, owing to the rapid response achieved, the alternator with a Magnicon exciter, whether with concentrated

salient-pole field or distributed field winding, can be designed with a lower ratio of field strength to armature reaction than for a conventional design. In the case of the distributed field winding, the ratio can be lower because its lower time-constant results in rapid response. However, I query whether the lower time-constant of the distributed winding would permit a great reduction in alternator frame size compared with a salient-pole alternator with Magnicon excitation, because of the poorer space-factor obtaining with a distributed field winding. Perhaps the authors would like to make some comment on this.

The statement in Section 4.6.2 does not line up with my experience. An increase of 4° C for an increase of copper losses in the ratio of 4 : 1 for the overhang, even making allowances for actual heat flow to the core, seems to be rather low. Moreover, I would consider that there will be also the transfer of the hot-spot temperature from the core to the overhang, thus making it more difficult to keep the temperature difference down to such a low level.

Mr. H. Du V. Ashcroft: I should like to ask about the conditions of the different brushes on the Magnicon. In the first stage the generated voltage is low so that the voltage drop at the brushes is comparable with the resistance drop. Does this not introduce non-linearity into the circuit? As the machine is designed for high armature loading I should expect it to be very sensitive to the brush position on the secondary axis.

Some years ago, I had experience of constant-current motors with characteristics between C and D of Fig. 1. On one occasion, after a disturbance a motor was found to be running at a point quite off the curve. It was found that the curves shown are halves of a hyperbola and that the machine was running on the reflected curve on the other side of the asymptotes. I should like to know whether the authors have ever met this condition.

Mr. J. M. Raven: I challenge the authors' statement in Section 4.1 that alternators cannot be compensated by series coils. A method of achieving this has been described by H. F. Storm.* The principle is similar to that of the conventional level-compound d.c. generator, except that the shunt and series excitation currents are combined in a transformer and rectified before being fed to the alternator field. By supplying the shunt winding from the line terminals through a choke and connecting the series winding in the load circuit, it is possible to derive a source of excitation which conforms very closely with the requirements of the alternator. The process involves matching the vector diagram of the transformer (which can be looked upon as a static exciter) with that of the alternator, bearing in mind that the terminal voltage, line current and excitation are vectors common to both diagrams. Virtually exact compensation for armature reaction can be achieved by this method, especially when used in conjunction with a distributed-field alternator of the type described in the paper. Judging by the authors' remarks in Section 4.1 this would also appear to be the sole function of the Magnicon. To my mind, the Magnicon does much more than this, however, and the authors would be belittling their own achievements to contradict me on this point. The essential difference between a compensated alternator and a Magnicon-controlled alternator is that the former is an open-loop system inherently sensitive only to the line current and its phase relationship with the voltage, whereas the latter is a closed-loop system sensitive to the ultimate quantity it is required to regulate. The fact that the Magnicon compensates for armature reaction is purely incidental.

Again, in Section 4.1 an analogy is drawn between the stability of a Magnicon-controlled alternator and that of an induction motor. I feel the analogy is being taken too far because the former is a closed-loop system while the latter is an open-loop system. The stability of all closed-loop systems depends upon the parameters of the loop and cannot be automatically relied upon without reference to the values of these parameters.

I have demonstrated to my own satisfaction that the Magnicon can hunt beautifully when used to control a salient-pole alternator. Open-loop systems, on the other hand, are inherently stable.

Mr. H. Ferry: Here we have a very useful method of control which up to the present has been applied only to relatively small machines. Could not the same technique be applied, say, to large turbo-alternators?

My second query concerns the characteristic of the Magnicon alternator, which follows the same shape as that of the conventional shunt generator, probably for much the same reason. The maximum current, however, seems surprisingly low. Is this due to saturation developing in the second axis of the Magnicon?

The systems dealt with in the paper are all closed-loop controls in which the reference is provided by a separately excited field, intersecting fluxes or critical speed, only the latter two being inherent properties of the machine. Under the circumstances, have the authors chosen the best possible title for the paper?

Mr. A. W. Hirst: Engineers accustomed to systems working at constant voltage and with varying current find great difficulty in thinking in terms of constant current and varying voltages, and for this reason I think that certain sections could well have been amplified.

As an example, consider Section 1.2, on the constant-current motor: a question which would immediately come in the minds of ordinary engineers would be, Where does the motor get its field from? It cannot be a series field since the excitation is varied by injecting an e.m.f. into the field circuit. I presume the field in series with the regulator armature is connected across a resistance placed in the main circuit, but many engineers would not be familiar with this arrangement and an amplified diagram would have made everything clear. This diagram would also have made Section 2.5.1 easier to follow: I must confess I did not quite follow it all.

Again, Section 2.6.1 is a masterpiece of compression, and possibly justified because the principle of the constant-current generator is fairly well known, but how a diagram would have helped in the next two Sections in showing the development of the metadyne and Magnicon.

Messrs. H. S. Hvistendahl and **J. C. M. Sanders** also contributed to the discussion at Loughborough.

* STORM, H. F.: *Transactions of the American I.E.E.*, 1951, 70, p. 1014.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. J. C. Macfarlane, J. W. Macfarlane and **W. I. Macfarlane** (*in reply*): In reply to Mr. Towle, the Kramer generator is still used variously for ship propulsion, supplying digger hoist motors and for similar drives where local holding is desirable.

In British Patent No. 362631 the authors describe modifications of the Kramer machine which have been considered for ship propulsion and for other purposes. Fully compensated continuous-current generators with completely laminated magnetic circuits may have natural oscillation frequencies of more than 50 c/s (those in Fig. 4 being about 30 c/s). Design is a matter of proportion.* If the exciter ceiling or forcing voltage is high enough the generators can be suddenly switched from full load

* MACFARLANE, J. C., MACFARLANE, J. W., and MACFARLANE, W. I.: "Direct-Current Arc Welding Generators and Systems," *Journal I.E.E.*, 1946, 93, Part II, p. 603. See Section 3.3.3.

to short-circuit without undue current oscillations or sparking at the brushes.

In reply to Mr. Tyrrell, Magnicon excitation enables simpler, more robust, less costly alternator systems to be provided when compared with the conventional automatic-voltage-regulation type; speed of response and amplitude of oscillation due to sudden load changes are much less, and no outside voltage reference is required. The short-circuit characteristic may be simply modified to suit any particular network.

In reply to Mr. Michael, the generator field time-constant is reduced with smaller air-gaps if the field-circuit loss is maintained. Smaller gaps also mean that, for a given saturation, the ratio of m.m.f. for iron to that for the gap is higher. Generally, therefore, the time-constants are smaller. A diverter across the interpoles has a similar effect to a closed circuit around the interpoles, but the former is easier to adjust in practice.

In reply to Mr. J. Hindmarsh, compensated constant-current generators designed to conditions (*b*) and (*c*) are not limited in size by small air-gaps, diverters or brush position, and the amplitude of the first swing when sudden short-circuit is applied need not be greater than twice full-load current if the field-forcing voltage is high enough and the generator design is suitable.

We thank Dr. Rosenberg for his historical notes on the application of the Rosenberg dynamo by Mr. J. L. Woodbridge to constant-voltage train lighting. The speed range over which the voltage remains constant (nearly four to one) is remarkable. With regard to centrifugal driving (Section 2.5.4), the starting and stopping was accomplished by a hand-manipulated diverter to the motor exciting coils. The average power delivered to the centrifugal basket during acceleration through a speed range of zero to 1 800 r.p.m. was approximately 60 h.p., and the basket was driven through a coupling sufficiently flexible to allow it freedom to gyrate and swing.

In reply to Mr. Westgarth, there is practically no limit to Magnicon size as a straight exciter, but the usual practice when such exciting schemes are applied to large generators is to use pilot exciters; this, by introducing another "stage," gives a higher rate of response and a physically smaller exciter.

The value of R (Section 9.1.2) should be 0·09 ohm, not 0·9 ohm as printed, and this accounts for the results obtained by Mr. Broadbent. We regret this and other discrepancies kindly pointed out.

In reply to Mr. Henderson, saturation in the short-circuit axis, to stabilize the Magnicon, is unnecessary since the effect of the positive feedback in the compensating winding, although anti-stabilizing, is relatively ineffective owing to the large inductance of the main alternator field.

We thank Prof. Tustin for his historical notes and are pleased to note that many of our recommendations, which are the result of experience, are consistent with the theories of an acknowledged expert.

In reply to Mr. Bassington, two conventional exciters in cascade will act in a similar manner to a cross-field machine. Elimination of the field winding of the second stage of the cross-field machine, however, makes the action faster and the control more rigid.

In reply to Mr. Easton, since the armature m.m.f. is opposed by an m.m.f. in the field structure of correct magnitude and shape, it is truly compensated as would be any cylindrical-rotor-type alternator having a sinusoidal field-m.m.f. wave. The salient-pole machine cannot have this and is not therefore truly compensated. The short-circuit ratios required are of the order of (*a*) 0·5, (*b*) 0·13, and (*c*) 0·175.

In reply to Mr. Huggard, anti-hunting coils are not required in the Magnicon, and this condition is relatively independent of the overall amplification and whether the Magnicon is used with small alternators having small time-constants or not. It is incorrect to assume that a salient-pole alternator automatically requires less field power than the Magnicon equivalent, since this assumption does not allow for the fact that the total field m.m.f.'s required may be (and usually are) vastly different. With reference to the 160 kW generator (Section 2.3), the oscillograms shown in Fig. 4 were taken from this generator and the frequency of oscillation indicated was approximately 30 c/s.

In reply to Mr. Wilcock, although it is possible for the magnetic-saturation point to vary with temperature, this is negligible in comparison with other possible variations. The possible limit of all variations when every precaution is taken appears to be about $\pm 1\%$. Relatively large harmonics are required to affect appreciably the (r.m.s. voltage)/(average voltage) ratio, and the output waveforms at all loads of Magnicon alternators are reasonably sinusoidal.

In reply to Mr. Whiteside, for a given voltage the control current, and therefore the alternator voltage, depends on the resistance of the control circuit, and this in turn depends on its temperature coefficient. Reduction of the circuit-resistance variation by the use of materials of low coefficient is usually sufficient since some help can also be obtained from the temperature coefficient of the rectifier.

In reply to Mr. Mare, by the use of conventional methods and apparatus, Magnicon alternators can be run in parallel with conventional alternators using automatic voltage regulators.

In reply to Dr. Thompson, since the frequencies of oscillation of such generators are so high (30 c/s as in Fig. 4), and severe damped oscillations can occur only under accidents of switching, the normal working of the system in service is not affected. The load on the circuit is highly inductive, consisting as it does mainly of motors, and normal switching transients do not disturb appreciably the constancy of the circuit current.

In reply to Mr. Scott, under abnormal conditions sustained oscillations are possible in any system of control, but they are rarely present in practice with Magnicon exciters, where, other things being equal, the ceiling e.m.f. of the exciter does not exceed the ratio 2/1 and where the positive feedback is in a high-inertia circuit.

In reply to Mr. Knowles, we think that when the a.c. system is being introduced for distribution on board ship, constant current for loads of varying speeds will be favourably considered, since a d.c. supply is undoubtedly the best for winch drives, etc.

In reply to Mr. Skenfield, there are many applications where a response time of less than 0·05 sec is necessary, and in the interests of standardization it is desirable to cover the whole range in one set of designs if possible. We do not agree that salient-pole generators are necessarily cheaper than the cylindrical type.

In reply to Mr. J. E. Macfarlane, because Magnicon excitation enables simpler, more robust, less costly generator systems to be provided, it will always be worth while changing from automatic voltage regulation to Magnicon control. Owing to slot skewing, care in the selection of winding span and the adoption of the largest practical number of slots per pole, phase-harmonic disturbance is practically non-existent in Magnicon alternators.

In reply to Dr. David Morris, on the constant-current system it is desirable to provide against accidental short-circuit of the generator when working near full load, and, if such occurs, to limit the transient peak current to approximately twice the line value. On this assumption the following occurs: (*a*) If the ceiling voltage of the exciter is high enough (for example six times) there is applied instantly to the main generator field a reverse e.m.f. six times that of the normal excitation (required for full load) to reduce the field current to zero. (2) It is easy to arrange for the armature to present instantaneously a transient

demagnetizing m.m.f. against the field equal at least to 50% of the full-load value.

In reply to Mr. Aldred, the cross-field principle could be applied to motors, but nothing would be gained because the standard d.c. motor is simpler and capable of operation through a wide range of speed. Ward Leonard control is used when conversion from alternating to direct-control is necessary, and it has the further advantage that a speed range from zero is available.

In reply to Mr. Jones, if field boosting maintains level voltage in the round machine, at any power factor, the field m.m.f. consists of two component vectors. One exactly balances armature reaction; the unopposed remainder supplies the flux. The axis of the total field m.m.f. does not coincide with the flux axis, and true compensation is achieved.

In reply to Mr. Maltby, Magnicon alternators can be supplied for a frequency range of $1/1 \cdot 5$ with direct-coupled exciters, the voltage control being within $\pm 2\frac{1}{2}\%$ at any setting. For larger ranges (say 3/1) a separately driven Magnicon exciter is preferable.

In reply to Mr. Parsons, the use of special low-loss iron for the Magnicon core is necessary to obtain close alternator regulation, i.e. less than $\pm 1\%$. Magnicon alternators have been used successfully for supplying power to X-ray apparatus.

In reply to Mr. Minchin, the iron losses of a Magnicon alternator are less than those of the equivalent induction motor because (*a*) it runs at synchronous speed and (*b*) the air-gap is usually about 50% greater, i.e. auto-synchronous-motor practice.

Although the copper loss is increased to 400% of its original value in a double-voltage generator, the iron loss (varying as the square of the flux density) is reduced by a similar amount. The total copper and iron losses at full load on each voltage setting are practically equal. The field/armature m.m.f. ratio when running at the lower voltage was approximately $1 \cdot 2/1$.

Mr. Price says, "An advantage of the distributed-field rotor is that the air-gap reactance is uniform and the resultant m.m.f.'s are not distorted by the armature-reaction quadrature component."

We are of the opinion that this is the description of a truly compensated machine, for in a suitably distributed winding the resultant m.m.f. becomes the difference of two (almost) sinusoidal m.m.f.'s, which favours the production of a sinusoidal working flux.

In reply to Mr. Ashcroft, there is a certain tendency to non-linearity owing to varying brush conditions, but this does not cause much trouble in practice because most of the control voltage during load variation is generated by the compound winding. With regard to instability of a motor giving a speed/torque characteristic between C and D, in Fig. (1), we feel that, owing to temperature or perhaps other causes affecting the relative proportions of the regulating-motor field windings, the actual characteristic lay temporarily outside ACB—an unstable condition.

In reply to Mr. Raven, we adhere to our statement that alternators cannot be truly compounded by series coils alone; there are no series coils on the field of H. T. Storm's alternator. The principle underlying this method is in fact to boost the alternator field by the correct amount as is done in the Magnicon, although the method is different. We are in agreement with Mr. Raven when he says that the superiority of the Magnicon lies in the closed-loop control. While it is possible to make a Magnicon hunt (when acting as an amplifier), when used with an alternator hunting is caused by maladjustment since the Magnicon response is slowed by series feedback in circuit with a large inductance—the alternator field.

In reply to Mr. Ferry, the output characteristic of the Magnicon is quite similar to that of a good shunt-wound generator. The maximum current limitation is due to saturation developing in the second axis of the Magnicon, and in view of the fact that Diesel-engine overload output is usually fixed at only 10% the maximum generator current reached is ample.

Finally, in reply to Mr. Hirst, we deliberately excluded consideration of the technical details of the constant-current motor for space reasons. The main-motor field is in series with the control-motor armature and both are connected across a dropping resistor in the main circuit. The following references may be useful.

(A) AUSTIN: *Transactions of the Institution of Engineers and Shipbuilders in Scotland*, January, 1924–25, **68**, p. 103.

(B) AUSTIN: *The Engineer*, 1928, **146**, p. 552.

DISCUSSION ON "THE TESTING AND SPECIFICATION OF BUSHINGS IN RELATION TO SERVICE CONDITIONS"*

SOUTHERN CENTRE, AT HOVE, 14TH OCTOBER, 1953

Mr. E. W. Connon: The development of power-factor testing of bushings on load is a great advance, because I have found by experience that a great deal of the time during testing is unproductively employed waiting for circuits to be made dead. The method which the authors propose is very neat, but I would like to describe a simpler method which has been used. In this method a single bushing on a switchboard is tested off-circuit by means of a Schering bridge in the ordinary way, and then all the other bushings on the switchboard are compared on load, by means of the Schering bridge, with this previously tested insulator. In effect, the "standard" insulator takes the place of the standard condenser, and the testing supply is from the switchboard busbars. This method is not, of course, as accurate as the more direct method proposed by the authors, but accuracy is not of great importance in site testing, since one is interested only in whether the bushings are good or bad.

Mr. L. H. Fuller: I found it rather tantalizing that little reference is made to the application of bushings or the design of the bushing surround or housing. I gained the impression that emphasis is laid on voltages above 33 kV, and whilst I agree that these are more important, I hope that voltages of 33 kV and lower will continue to receive designers' careful attention, as we still have failures from time to time, and not always on old equipment.

I am interested to learn of the inadequacy of some porcelain sheds to stand up to the rain tests, although I do not understand what this has to do with s.r.b.p. bushings; but I suggest a better test might be the effect of London "smog" or the Brighton seafront.

With regard to Figs. 8 and 9, I wonder whether the ionization would have been delayed had there been no voids between the bushing and the conductor. On examination of some of these insulators, it appeared to me that they sectioned rather easily, coming apart in what appeared to be definite packets of paper about $\frac{1}{8}$ in thick. I assume that a modern bushing would be more closely married, possibly with more resin content.

Can it be assumed that curve (*d*) of Fig. 5 indicates a bad bushing? On consulting the records, I find a power-factor range of some 5 : 1 over the bushings in a single circuit-breaker, and in no case was the high-value insulator unsound.

Mr. E. K. Dalby: I consider that the authors have made an excellent case for the complete abolition of the dry 50 c/s withstand test and the conditional dropping of this test under wet conditions. My experience in these matters is confined to the impulse testing of overhead-line insulators, and I am convinced that these tests will furnish all the information required. For reasonably accurate insulation co-ordination, the impulse flashover voltage must be known; impulse testing for this purpose is an obvious choice. It would also indicate any weakness or defect.

With reference to rod-gaps as used with bushings, and with due regard to the inherent advantages of simplicity of design, I am surprised that more has not been done to limit the associated discharge lag. Lightning-arrester manufacturers claim that this is of the order of 2 microsec, as against 1 microsec for typical solid insulants on adjacent equipment, and compared with less than 1 microsec for lightning arresters. I consider that the answer to this problem lies in better electric-field uniformity in the gap. Perfect field uniformity could reduce this time to 0·01 microsec. From practical experiments in this direction I am convinced that near-perfect uniformity is impossible with bare electrodes and the large ratio of gap length to electrode diameter required under conditions of service (the use of graded-permittivity insulation could rectify this).

The authors' reference to longitudinal weakness compared with the radial electric strength of condenser bushings will surprise no one, and in testing a similar arrangement of insulation without conducting foils, as used in h.v.-cable paper tube joints, I have been surprised at the extent of this discrepancy.

The complacency that exists regarding discharges in bushings appears to be based upon the fact that these largely disappear, presumably owing to reduction of insulation resistance at the source. They must, at least, produce inductive radio and television interference in the immediate vicinity. However, I think that those discharges undetectable by an a.c. discharge instrument of modern design, and due to valve noise and external interference, are of academic significance only.

As a means of improving the signal/noise ratio of the instrument, I suggest the use of a pre-amplifier on the bushing with cathode-follower output feeding a balanced, push-pull, or cascade input circuit on the remote main amplifier.

[The authors' reply to the above discussion will be found on page 410.]

WESTERN CENTRE, AT BRISTOL, 9TH NOVEMBER, 1953

Mr. C. R. Drummond: When extensions are made to an existing bank of switchgear which is perhaps ten years old, what reduction in the 1 min alternating-voltage test would the authors advise, and in what proportion should this test be reduced for still older switchgear?

Mr. C. J. R. Blackett: Why do some manufacturers place arcing horns on the underside of an outdoor bushing when such a bushing is inclined away from the vertical? It seems that, should these horns arc over, the arc would be carried upwards and probably damage the bushing; whereas if they were placed above there would be a chance of the bushing being undamaged.

Mr. N. G. McCullagh: It has been my experience that bushings, especially indoor types, often suffer severely, both in handling and storage conditions, before they are commissioned, and I feel that this, rather than manufacturing errors, may be the primary cause of later trouble in the rare cases where that occurs.

The authors refer the "knee" of the power-factor curve to a working voltage $E/\sqrt{3}$. I have met specifications which refer this to E; this would seem uneconomic and unnecessary on earthed

* Barker, H., and Davies, H.: Paper No. 1460 S, February, 1953 (see 100, Part II, p. 427).

systems, and I should welcome the authors' views on present acceptance specifications, particularly at 11 and 33kV.

The authors mention the usefulness of 10kV Schering-bridge equipment for testing in the field, and I should be interested to know the maximum system voltage they have in mind.

With regard to the positioning of arcing horns on the underside of outdoor bushings which are not vertically mounted, I think this is usually done to maintain maximum phase-to-phase clearances, which would be reduced by the top arcing horns if these faced one another.

Mr. E. H. T. Jewell: I am particularly interested in the authors' experiences mentioned in Section 3.4, where it is suggested that, in some cases of s.r.b.p. deterioration, erosion takes place, at any rate in the earlier stages, without the formation of carbon tracks.

I have experienced a case of incipient failure in a 132kV condenser bushing where the erosion had penetrated through at least one of the condenser foils. However, on subjecting the faulty unit to a Schering-bridge power-factor test in the laboratory, a reasonably flat power-factor/voltage characteristic was obtained up to a voltage well above the normal rating. This experience seems to support the theory of erosion without an accompanying carbon track. If this can be the case, great importance attaches to the electronic test for internal discharge, mentioned in Section 4.2.5.

A very reasonable case has been made for the abolition of over-voltage tests in favour of impulse-withstand requirements, and I think that this course is amply justified, bearing in mind the type of dielectric under consideration and the weakening effects which over-voltage tests may have without disclosing any defects at the time of testing. The reasons for reaching this conclusion would have been more apparent had Fig. 1 been provided with a gap-spacing scale extending up to 38in. I am surprised that in Table 2 a 1min over-voltage test has been retained for bushings of 66kV and above, at variance with the authors' arguments.

Mr. L. F. M. Baker: Can insulation tests, carried out periodically on bushings, afford any useful indication of deterioration and enable a bushing to be taken out of service before breakdown takes place?

I gather that the authors do not consider that the sensitivity of instruments such as the Forrest tester permit the measurement of falling insulation resistance to a degree sufficient in most cases to detect a dangerously lowered power factor in time to prevent trouble.

Mr. G. O. McLean: Supply engineers are now considering the increased loading of transformers, which will entail hot-spot temperatures of 110°C and top-oil temperatures of 90°C. What is the critical temperature for resin-bonded-paper bushings, and is the instability point near 90°C? If the critical temperature is near 90°C, would the use of silicone-varnished paper be a solution?

Mr. W. H. Campbell: It is probably true that more than half of the 132kV bushings in service at present are between 15 and 20 years old, and a considerable number have been in service for more than 25 years. It would seem only prudent to have these older bushings routine-tested for power-factor and ionization characteristics. Sooner or later these bushings will fail, and some warnings of approaching failure could be most useful.

The authors' confidence in new 132kV bushings is no doubt amply justified, but such confidence has yet to be earned for 275 and 380kV units. Just as all the hazards associated with 132kV working were only imperfectly appreciated 30 years ago, so at present may be those of 275 and 380kV designs. Although methods of manufacture have been greatly improved, deterioration owing to ionization is bound to occur in resin-bonded-paper bushings even if at a slower rate, and one would expect the achievement of thermal stability to present greatly increased problems in bushings designed for the superimposed Grid voltages. Therefore, I think that some means and system of routine testing on site should be regarded as not only possible but essential for these installations. Considerations of economy would point to the possible use of the on-load equipment for power-factor testing, and perhaps the authors would develop a little further the question of the application of such apparatus. Experience at 132kV seems to suggest that plotting comparative power-factor/voltage curves directly up to the working over-voltage is most desirable for investigating the ageing characteristics, but if Fig. 6 can be taken as typical, possibly single readings of power factor would suffice on site, coupled with some form of electronic ionization tests.

[The authors' reply to the above discussion will be found on page 410.]

NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 8TH DECEMBER, 1953

Mr. H. Shackleton: Twenty years ago it was suspected that internal ionization was taking place in many 33kV metalclad switchgear bushings which had been in service for varying periods up to 11 years in a large substation. Some of the earlier bushings were of the 3-foil type, whilst others of later manufacture had eight foils. The manufacturers were consulted with a view to deciding on a testing procedure which would indicate the bushings that should be changed. Power-factor measurements on site at that time were impracticable, and it was also concluded that high-voltage tests alone were undesirable because of the danger of inducing internal discharges and thus producing conditions favourable to gradual failure. Moreover, unless fairly high voltages were employed, it was unlikely that breakdown would occur in a short space of time. It was finally decided that the aural determination of the hissing point by application of high voltage was probably the most dependable test that could be simply applied. Periodical tests were to be made to determine the presence of discharge at working voltage (i.e. 19kV to earth). Any bushing giving aural evidence of discharge under working conditions was to be regarded as suspect and removed for careful examination. Dissection of some of the suspected bushings showed that those which hissed at normal voltage were deteriorating, the insulation being furrowed quite deeply in places, but there was little sign of carbonization. It was not uncommon in those days to find evidence of faulty manufacture. For example, a layer of paper would be found to have rucked during manufacture of the bushing, and the paper to have been folded upon itself. Unsatisfactory adhesion between the layers of material was also found at the point where the centre foil had been inserted.

Whilst manufacturing techniques have improved considerably during the last 20 years, the problem of devising a simple test to enable us to determine with some accuracy the expectation of life of a bushing still remains. Only a very rough guide can be obtained from field tests of power factor, taken usually well below the working voltage, unless records of performance covering a number of years are available. Unfortunately comparative data of the power factor at the time of installation are not available for many of the bushings in service to-day.

In Section 4.2.3 it is stated that the power-factor/voltage test is probably the most useful of all tests for s.r.b.p. bushings, but that it cannot distinguish between a rise of power factor owing to ionization and one from other causes; the method is also relatively insensitive in detecting internal discharges.

In Section 6 it is stated that a power-factor test may not indicate slight local internal discharges or the presence of localized pockets of moisture, but it is reasonable to expect that any deterioration of the insulation arising from these causes will have an effect on the power-factor/voltage characteristic long before the insulator reaches a dangerous condition. It is desirable to know the period of warning we are to expect, since this determines the frequency of testing and also the expectation of life.

Bearing in mind the difficulties which arise in the removal of many bushings, what is the authors' opinion on the action that should be taken and its urgency, where internal discharges are detected at or just below working voltage?

In Section 6.1.1 it is stated that the majority of site tests are made with a portable 10kV Schering bridge, and very often an indication of the shape of the full power-factor/voltage curve can be obtained by taking readings up to this voltage even on systems with voltages of 33kV and higher. I cannot reconcile this statement with the curves shown in Fig. 5, where if $E = 33$kV, 10kV is represented by the fourth ordinate from the left.

It is quite common practice nowadays to use 33kV feeder transformers, the transformer being provided with links to enable the windings to be disconnected from the cable for testing purposes. Even so, at least three bushings are energized when the cable is subjected to a power-frequency voltage test, which for a 33kV cable would involve the use of a direct voltage of 66kV to earth for 15min. Have the authors any objection to such a test being applied to the transformer bushings? The test period specified in B.S. 116 is 1min, although I understand the German V.D.E. rules require 5min in the case of fibrous materials.

In E.R.A. Report Ref. L/T134 it is stated that in some cases there is a danger of serious over-stress on one of the insulating components of composite insulators, but in the majority of insulator assemblies there will be no material difference between a.c. and d.c. stress distributions. I should welcome the authors' views on the subject of d.c. testing of bushing insulators.

In Section 3.5 it is stated that the resistance of an insulator to service deterioration is mainly dependent on the surface-varnish finish. This applies, of course, to all resin-bonded materials, and there is a theory that ultimately, owing to ageing, the surface-varnish cracks provide lodgment for any carbon and result eventually in treeing and subsequent failure of the insulator. Have the authors had similar experiences with surface varnish on bushings?

Fig. 5 indicates various forms of power-factor/voltage curve, and with curves (*a*), (*c*) and (*d*) it is not difficult to detect the knee point, but curve (*b*) is rising slightly below normal working voltage, and it would be interesting to know how the knee point is then determined.

In tests on new bushings, variations of about 5% in power factor between 0·58 and 0·75 of the working voltage have been experienced, and I should welcome the authors' views on whether such bushings would be considered satisfactory.

Curve (*d*) of Fig. 5 indicates a bushing, the power factor of which is abnormally high owing to moisture content. It would be useful if the authors would indicate the tolerance which could be allowed on new bushings for similar units at the same voltage and temperature. Instances have occurred where the range is about 130%, with over 50% variation from the mean value. The authors state that power-factor/voltage curves are indicative of defects other than ionization, e.g. internal conduction through a puncture of a condenser layer. Can the authors confirm that the power-factor test would indicate such a defect, as I was under the impression that a capacitance test was necessary for this purpose?

In Section 7 it is stated that it is unnecessary to carry out routine tests of modern insulators on site, and it would be interesting to know whether on 33kV switchgear the authors would suggest omitting any provision for such testing.

Mr. P. G. Ashley: Fig. 6 shows discharge curves with a definite extinction voltage, and I have previously indicated* that results such as these are not always obtained. Much depends on the sensitivity of the discharge bridge, and until agreement has been reached on sensitivity it is unwise to make comparisons. Fig. C

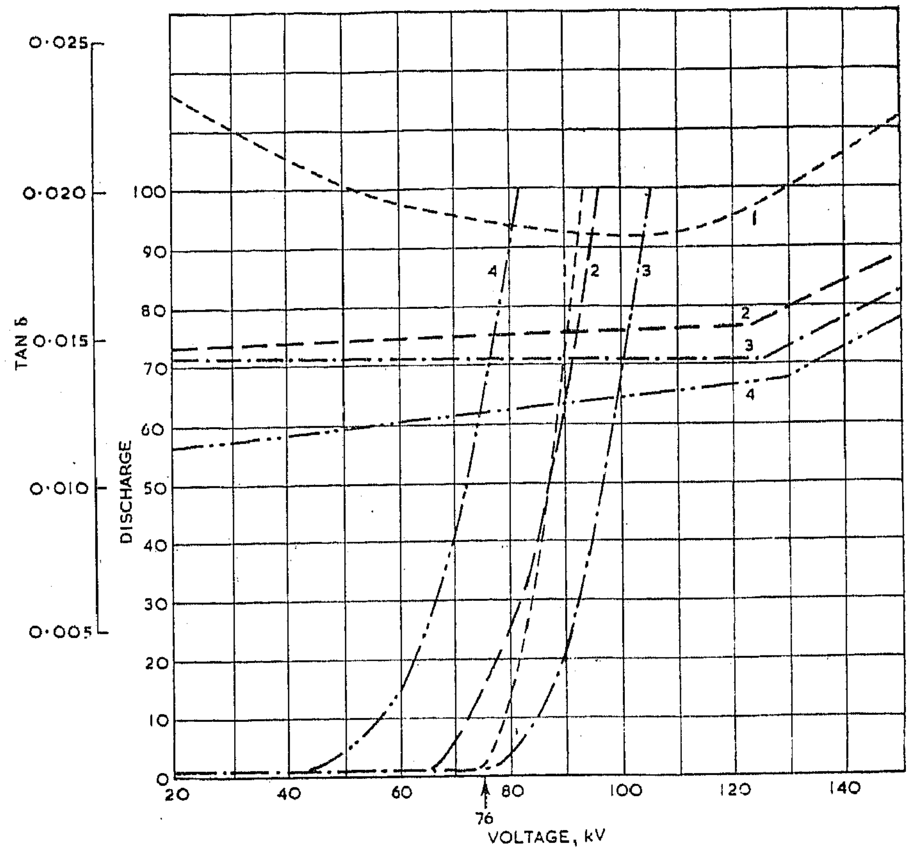

Fig. C.—Results of tests on 132kV bushings which have been in service for some years.

At 76kV

Bushing No.	Equivalent internal discharge	tan δ
	μμC	
1	165	0·0186
2	825	0·0150
3	0	0·0140
4	3 300	0·0124

shows some results of tests on 132kV bushings which have been in service for more than 20 years, and it will be noted that bushings Nos. 2 and 3 have a normal shape of the tan δ/voltage curve, although it is higher than would be expected for new bushings. Curve 4 indicates some inferiority as compared with curves 2 and 3, but this bushing will probably respond to drying-out, after which I should expect the shape of the curve to be more normal. Curve 1 indicates some internal fault, and a step-by-step examination of this bushing revealed that one dielectric layer was punctured and another had a very high value of tan δ. However, it must be noted that the equivalent internal discharge for bushing No. 1 at 76kV was only 165$\mu\mu$C, as compared with 825$\mu\mu$C for bushing No. 2; and that bushing No. 4—which is not greatly at fault—has 3 300$\mu\mu$C of equivalent internal discharge. None of the bushings have failed in service, and I consider that, although freedom from internal discharge at working voltage is a condition for which we are all striving, it is not essential for safe operation over many years.

I agree that regular tan δ tests in service are not universally essential. In my opinion, the need is less for bushings totally

* *Proceedings I.E.E.*, 1953, 100, Part II, p. 441; *ibid.*, 1953, 100, Part IIA, p. 176.

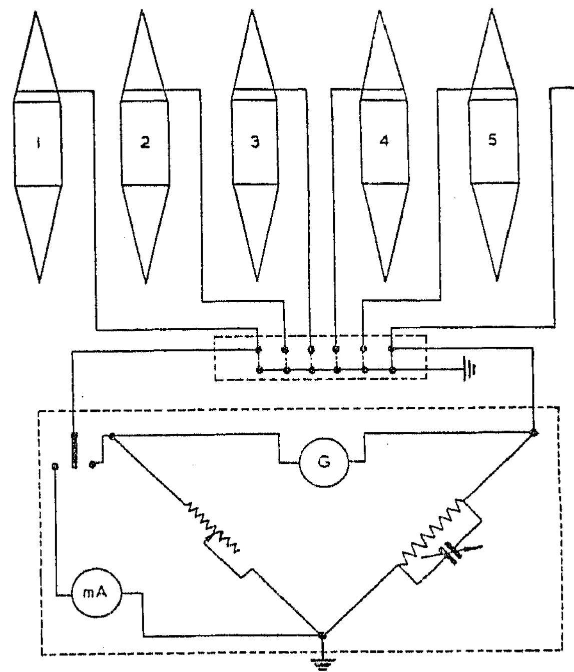

Fig. D.—Bushing comparator.

immersed in oil than for those which are exposed to air. Where service testing is desirable, I have used a bushing comparator, as shown in Fig. D. The earthed ends of the bushings are taken to a terminal board where they are normally earthed. The comparator consists of a milliammeter and a Schering-bridge ratio-arms box. By means of suitable plugs, the milliammeter can be connected to any bushing to provide periodic records of the charging current. Similarly, the ratio-arms box can be connected to two bushings as shown, so that measurements may be made of the difference in tan δ for the two bushings. In the diagram, bushing No. 6 acts as if it were the standard condenser, and thus it becomes the reference bushing against which the others can be compared. Whilst there may not be a linear relationship between tan δ and charging current, an increase in tan δ is usually accompanied by an increase in charging current at any given voltage, and in some circumstances this might focus attention on a particular bushing, which might repay investigation. If one bushing during periodic measurements shows a marked increase in charging current and in tan δ as compared with others of the same design, arrangements may be made to isolate that bushing and investigate it further.

Mr. R. G. Torry: It is suggested that it is desirable to include in the test specification requirements to ensure that a bushing will perform in a satisfactory manner, not only as a separate entity but also situated in the position which it will occupy under service conditions; e.g. in a circuit-breaker or transformer tank. In this condition the stress distribution may be affected by the proximity of adjacent metalwork to such an extent as to reduce the ability of the bushing to withstand the required test performance.

Allowance should also be made when testing air-immersed bushings to take account of the relative humidity of the air; and attention should be given to site altitude, which, if high, will affect the density of the atmosphere and thus corona effects and flashover voltages on site, as compared with test results at sea level.

When considering wet flashover tests it should be realized that wet conditions will most likely be a cause of changed stress distribution and may even (in a particular design of bushing) so alter the stress distribution that the power-frequency wet flashover voltage is actually raised to a higher value than the dry flashover voltage. It is desirable to retain wet flashover tests for this reason and also as a check on the possibility of a flashover cascading over the surface of the insulator.

It is highly desirable to test the ability of the porcelain weather-shed, complete with its metalwork fittings, to withstand sudden temperature changes. The temperature-cycle test can be used for this purpose, but there is some doubt whether an incipient crack in porcelain can always be detected by the normal methods. Supersonic testing is not well adapted for this purpose. Do the authors know any method of testing which can be used to reveal such cracking?

Dr. H. F. Maass: There is a fundamental weakness in the way that the relationship between service conditions and a specification for bushings has been dealt with. Section 5 conveys the impression that this relationship consists of an extended list of proving tests only. That is rather putting the emphasis on the wrong side and is far too narrow a view. For instance, the revision of a specification should take account of cumulative service experience. Bushings of British manufacture have given good service, even though they have been produced to what is now an inadequate specification. In this excellent service record there have been very few blemishes, and the majority of such trouble has not been associated with matters covered in the existing British Standard. Occurrences like a cracked weather shed, a gasket admitting moisture in time and a surface finish which in the long run suffers from moisture and bad pollution combined, would, however, not be obviated by the authors' proposals. My conclusion is that a specification cannot eliminate the necessity for the special skill of the manufacturer. The manufacture of bushings is a highly developed technique and requires a wide background of experience. This could in no way be replaced by a long string of tests. Basically, a specification has to define the requirements the bushing is to meet in service and its application together with other gear. Such a definition of requirements does not by itself necessitate proving tests. However, tests have to be made to check design and manufacture. Thus provisions for certain widely-recognized tests are a most useful part of a specification.

Still, and this cannot be overlooked, there remain service conditions which manufacturers have to take care of, even though tests suitable for proving purposes have not been evolved, as distinct from investigational test methods which can be very valuable indeed. The effects on bushings of moisture penetration and surface deterioration are an example of this situation.

With regard to other service stresses the position is that, whilst tests have been evolved, there is neither sufficient information about them nor general agreement on their usefulness for proving purposes. Such tests should not be admitted if development is not to be hampered. The information given by the authors on the under-oil impulse-withstand test is rather meagre and hardly convincing. In connection with the internal-discharge test, it is stated in Section 4.2.5 that further work is required.

In selecting proving tests one cannot lose sight of the cost. This increases the price of an article, the quality of which depends on manufacturing skill as much as on any specification.

Mr. C. H. Berry: With regard to the statement in Section 3.5, why do the authors wish to confine the use of anti-tracking varnishes to exceptionally severe conditions? In my experience it is not uncommon, especially on low-voltage air-insulated switchgear, for the switch houses to be inadequately heated and ventilated. Whilst the onus for suitable conditioning is the responsibility of the user, every precaution should be taken to prevent surface tracking by the use of anti-tracking varnishes for all exposed s.r.b.p. bushings. With regard to the evaluation of varnishes for this purpose, the more well-known tracking tests have definite limitations in relating the performance of a surface finish to service conditions. The organization with which I am associated has developed a method of testing which simulates some of the worst conditions that may be found in practice. This test consists of an accelerated life test under conditions

involving high humidity, dust deposition, nitrous oxides and ozone. Sample treated bushings are subjected continuously to these conditions, whilst being energized at line-to-line voltage in a special test chamber. Although it may take some months to obtain the required information, the results are representative of what may occur in service over many years. The test enables the tracking resistance and the moisture resistance of the materials and varnishes used in bushing manufacture to be evaluated, so that the best-known finish and material can be used. An interesting feature of the test apparatus is that the atmospheric conditioning of the test chamber is obtained naturally without the aid of heaters or humidifiers by using, for the test chamber, a converted underground concrete air-raid shelter. It has been found that the humidity remains at about 90% relative humidity and the temperature at 16°C throughout the year. Variations can be obtained by controlling the ventilation.

The authors have described a scheme for on-load power-factor testing of s.r.b.p. bushings. An alternative method which I have used successfully on 33kV metalclad switchgear may be of interest. As with the authors' scheme it is necessary for the bushings to be provided with facilities for inserting between the low-voltage electrode and earth a resistance arm of a Schering bridge or similar test equipment. It is important to note that with on-load testing the bushing low-voltage electrode must not be left "floating" at any time. Before removing the normal earth connection, the low-voltage electrode of the bushing should be connected to earth through the testing equipment.

If the low-voltage electrodes of two bushings on load and in the same phase are connected to a Schering bridge, using one of the bushings in place of the usual standard condenser, it is possible to measure the difference in power factor between the two bushings and so note any changes that take place. It is not essential to know the actual capacitance and absolute power factor of the bushings to note any changes, but these values are sometimes useful. They can be found if the actual power factor and capacitance of one of the bushings used in the test are known. If a circuit-breaker bushing is used as one of the bushings under test, this can be isolated from the supply at some convenient time, and its power factor and capacitance can be checked by the normal off-load Schering-bridge method using a standard condenser and a separate h.t. supply. Any bushing in the same phase as the circuit-breaker bushing can then be checked against the circuit-breaker bushing with the two bushings on load, and the actual power factor and capacitance determined.

In Section 7 the authors state that on modern insulators made and tested to the standards laid down in the paper it is unnecessary to carry out routine testing on site. This statement is contrary to the practice recommended in B.S. 1086, which emphasizes the need for periodic checking on the condition of insulation. Surely the conditions prevailing on site determine whether routine tests are necessary rather than the performance shown by tests at the manufacturers' works.

Mr. F. S. Edwards: The data given in Figs. 3 and 4 would be enhanced if the approximate time of stressing during the tests at 50c/s were included. Can the authors supply this information?

Table 1 does not seem to be self-consistent, as the 1 min over-voltage test values in column 3 are substantially lower than the wet-withstand values in column 8.

In Section 4.2.1 it is stated that the routine over-voltage test originated as a means of eliminating faults giving rise to thermal instability. By making certain reasonable assumptions it can easily be shown that if the bushing is of uniform quality it will have to be almost impossibly bad, with a value of tan δ of the order of unity at the test temperature, for thermal breakdown to occur in 1 min on the usual voltage test. Even the poorest of bushings (judged by present standards) has a very large margin of safety against breakdown of this kind.

It is stated in Section 6.1 that it was not until the 1930's that power-factor measurements were made on bushings on site. It should be recorded that a 5kV portable Schering bridge was in active use in this country in 1929.*

There has been some discussion on the value of power-factor tests on high-voltage bushings at voltages well below the working voltage. There is no doubt that the value of such tests is restricted at the lower voltages, but when site testing was first introduced, the requirements of ease of transport and speed of measurement made a high voltage impracticable, and furthermore, the faults then frequent in bushings could often be readily shown up even at 5kV. The general quality at present is so much better, and the standard of performance expected is so much higher, that more refined methods of discrimination are now needed.

Mr. W. A. McNeill: One of the main problems which has delayed progress has been the under-oil puncture or flashover test. One school of thought advocates an impulse-voltage test only, but there are other advocates in favour of retaining the power-frequency basis. At the present rate we shall end with having both types of test, and achieve nothing except additional delays to production.

I am glad to see that the authors favour the impulse-voltage test, but note that the test voltages they propose are sufficiently high to ensure that a given bushing will automatically withstand the power-frequency test if it has proved satisfactory on impulse. I would have expected that an impulse-voltage test level, based on the insulation co-ordination of a system, could in some circumstances result in an economy in material, and I should be interested to have the authors' comments.

Mr. W. B. Robertshaw: I have had several years' experience of leakage testing by compressed air, and I have not known any instance of a bushing so tested being returned from service owing to an oil leak. The organization with which I am associated recently co-operated with consulting engineers in an experiment designed to assist in assessing the relative merits of the air test as against the traditional oil test. Of the bushings tested, two began to leak slightly within one hour of the commencement of an air test at a pressure of 10lb/in^2, while the remaining samples completed one hour without apparent leak. The complete batch was then subjected to an oil test for 24 hours at 10lb/in^2 pressure and 75°C temperature. All the bushings successfully passed this test. The indication is therefore that the air test may be more searching and can be of shorter duration. A quarter of an hour per foot of paper length has been tentatively suggested as a suitable duration. It is suggested that the air test, if acceptable, would by its speed and convenience benefit all concerned. It might be included by arrangement between manufacturer and customer as an alternative to the traditional oil test for types where at least equal sensitivity has been demonstrated and where ease of observation is possible.

Mr. W. Watson: With regard to Figs. 1 and 2, which record the wet and dry flashover characteristics of bushings fitted with rod-gaps at various settings, I note that the tests were made using 132kV bushings only. Do the authors consider that test results obtained by such a method may be considered to be fully representative, since a 132kV bushing fitted with arcing horns set at only a few inches can hardly represent a bushing for, say, 22kV?

On examining Fig. 3, which deals with the axial breakdown of s.r.b.p. tubes, I am rather surprised at the impulse ratio of about 1·1 obtained on the shorter axial lengths; I think this figure is on the low side. We have done a certain amount of work on this subject, and have found that, on short axial lengths, impulse

* *Electrical Engineering*, April, 1934, p. 168.

ratios of at least 1·4 are to be obtained, and in one particular case an impulse ratio in excess of 1·7 was recorded.

The bushing on which this figure was recorded was machined down and carefully examined at the conclusion of the tests, and whilst no signs of axial distress could be found, there were faint but unmistakable signs of incipient damage radially. This did not, however, amount to breakdown between foils and must have occurred at radial stresses considerably below the figure obtained by using the impulse-breakdown-voltage/thickness curve of Fig. 4.

Mr. H. L. Thomas: In the formulation of the impulse air-withstand values given in Table 1, has due regard been paid to the impulse test requirements of transformers with which the bushings may be used? It would appear that the values quoted in the Table are in general agreement with existing or proposed standards for the full-wave impulse test levels for power transformers, and indeed it seems likely that this is in fact the basis of the bushing impulse air-withstand proposals. However, it must be borne in mind that the transformers have also to be subjected to a chopped-wave test, for which purpose voltages 15% above the full-wave values are applied. Do the authors consider that in the design of bushings to meet the impulse air-withstand values specified, there is likely to be a sufficient margin to avoid the possibility of flashover at 15% above these levels? Actually, a bushing flashover during the chopped-wave impulse test on a transformer does not necessarily vitiate the test, but obviously it would be preferable for the chop to occur not on the bushing but on the properly standardized rod-gap which is provided in the test equipment.

Messrs. B. N. Hardy, J. E. Adey and **J. F. Dunn** also contributed to the discussion at Manchester.

[The authors' reply to the above discussion will be found overleaf.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 14TH DECEMBER, 1953

Mr. D. Riach: I cannot agree that, as over-voltages at power frequency do not occur in service in excess of the phase-to-phase voltage of the system, power-frequency over-voltage tests are of little value. It is quite a common condition for steam-turbine-driven generators to be run for extended periods without their automatic voltage regulators being in commission. If the generator is tripped on load the voltage may rise to 50% above normal. At this value the voltage to earth will be 0·87 instead of 0·58 of the normal phase-to-phase voltage. In these circumstances the duration of the over-voltage is dependent on the action of the operator. The same cause of over-voltage with water-wheel-driven generators will result in higher over-voltages owing to greater overspeeding. Surely the 1 min power-frequency over-voltage tests in the various British Standards for composite equipments like switchgear, etc., provide the necessary factor of safety to cover this contingency better than would be the case if impulse testing were substituted, as the latter does not simulate the duration factor of a power-frequency over-voltage. If it were decided to dispense with power-frequency over-voltage tests for bushings, I would emphasize that B.S. 223 was based on the power-frequency over-voltage test values in the British Standards for switchgear, transformers and cables with an appropriate margin added. I think, therefore, that the first logical step involves getting these British Standards changed before B.S. 223 can be changed.

[The authors' reply to the above discussion will be found overleaf.]

NORTH MIDLAND CENTRE, AT LEEDS, 2ND FEBRUARY, 1954

Dr. E. C. Walton: With reference to the condition of thermal instability in a dielectric, the statement in the first paragraph of Section 3.3 is, in my view, rather misleading. With any device in which energy is being dissipated as heat, the mean temperature continues to increase until the rate of heat dissipation to surrounding media rises to the level of the internal power dissipation. Then, and only then, does the temperature become stable. With a dielectric in which the rate of energy dissipation (owing to losses) increases appreciably with rise in temperature, the conditions may be illustrated by Fig. E. Curve (i) gives the

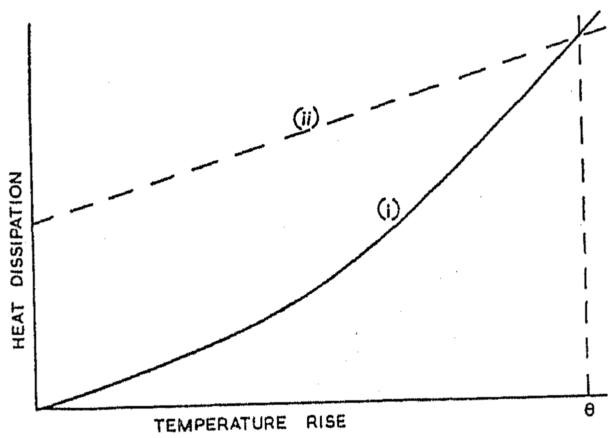

Fig. E

relationship between the rate of heat dissipation from the dielectric to surrounding media and the temperature rise. Curve (ii) relates the power loss in the dielectric under specified electrical conditions with the temperature rise. The point of intersection of these curves gives the estimated steady temperature rise, θ, attained under these conditions. If θ is sufficiently high, or if curves (i) and (ii) diverge so that stable conditions are unattainable, damage to the dielectric occurs and breakdown ensues. The authors do not state the temperature at which the test results depicted in Figs. 3 and 4 were obtained. It would be interesting to see some curves plotted from the results of the thermal-stability tests on the h.v. bushings referred to in Section 4.2.2.

The authors state in Section 6.1 that they regard the power-factor tests as the most informative of all site tests for bushings. Whilst this may be so, I should have thought that data might also have been given on the actual power losses occurring in bushings. From both power-loss and power-factor data it is possible to detect any changes in capacitance. Have such changes been investigated in connection with bushings? Is it possible that such changes may be responsible for the decreasing power factor indicated by curve (*e*) in Fig. 5 of the paper?

Mr. A. J. Coveney: I disagree with the authors' statement that the temperature may be no more than 60°C on bushings used in switchgear. With heavy-current switchgear, a permissible rise of 50°C over an ambient temperature of 35°C is allowed, and where the insulation is in direct contact with the conductors, higher temperatures will be possible. It would be interesting to know what the power-factor loss would be in Fig. 7 for, say, an additional 30°C rise, since curves already show a 100% rise between temperatures of 20°C and 40°C.

I agree that site tests are often made on a number of insulators in parallel, and the readings may be misleading, but can the authors give any indication whether there is an approximate

rule which can be applied to site tests, since a decision often has to be made from these whether an insulator must be condemned or not, and the curves shown in Figs. 10 and 12 indicate a large difference between site and works tests? It would be interesting to know also the position on the switchgear of the insulator covered by Fig. 10.

With regard to Fig. 14, it would be costly to provide test terminals with suitable plug-and-socket connection for the testing of each individual insulator. It is a question of economics, but I agree that it is worth while for insulators on important busbar installations. The auxiliary winding appears to be superfluous, since I do not see why the standard 110-volt secondary winding should not be used.

Mr. W. Plumb: From my own experience, the thermal-stability test is the one which gives most information on the subsequent performance of a bushing, and is of more value than any of the other tests which are applied for various reasons. This power-loss test curve is normally plotted against the application of over-voltage under certain conditions, principally of temperature, but I do not think that sufficient thought has been given to the question of the time applicable to this test. I agree that extended time tests cannot be accelerated and may therefore be difficult to carry out, but I am convinced that more attention should be paid to the voltage/time characteristic of all insulation than has hitherto been given.

Is there any possibility of an agreement with the United States on the question of the waveform applicable to impulse testing? In my opinion, the American method of $1\frac{1}{2}/40$ microsec is less arduous than our own 1/50 microsec waveform, particularly owing to the increased length of the tail in the British method. I should like the authors' opinions as to why no measure of agreement has been obtained to reconcile these two methods; and is the difference of 10 c/s in the power frequencies a reason for the differing impulse wavefront being selected?

Mr. A. R. Rumfitt: The tests described in the earlier parts of the paper are submitted on the basis of their influence on the authors' recommendations for a revised bushing specification. Therefore, it would seem justifiable to analyse the results obtained from these tests to find out whether the authors' conclusions are justified. At this point we encounter difficulty in that the graphs, shown in Figs. 5, 6 and 7 respectively, do not compare identical bushing performances. In the first case, we have a graph relating to a bushing for use at an indeterminate voltage reference E; in the second case graphs are given for a 132 kV bushing, and in the last case for a 22 kV bushing. Therefore, unless we are assured that all these bushings are constructed from identical s.r.b.p. material we have no true basis for performance comparison.

This difficulty of assessment is more clearly evidenced when we consider that, in Fig. 5, curves (*a*) and (*b*) are submitted as being those for bushings having an ideal power-factor/voltage characteristic at ambient temperatures, whereas the curves in Fig. 7 show a marked deviation from these figures at the ambient temperatures and a pronounced deterioration with increasing temperatures.

In Section 4.2.2 the question of moisture absorption is dismissed as being a thing of the past, with the implication that such troubles will never be encountered with present-day materials. The authors do not, however, give any sound reasons for their confidence in this respect. I submit that the higher power loss at elevated temperatures, shown in Fig. 7, indicates that the bushing material is undergoing some change. This may render the bushing liable to high moisture absorption when a rapid temperature drop is associated with an increase in the relative humidity of the surrounding atmosphere. It would seem that the authors should have indicated the relationship between electric strength and the moisture-absorption properties of the materials used in s.r.b.p.-bushing construction, and whether different grades of material are available by which high electric strength can be obtained by sacrificing resistance to moisture absorption and vice versa.

In Fig. 6 it is significant that the internal discharge value determined by the electronic method is given in arbitrary units. In the absence of details of the precise method of measurement, is it possible to state whether the results of such tests are truly comparative and reproducible so that check tests on site can be compared with the tests carried out under controlled laboratory conditions?

Mr. E. Bratton: The authors suggest 90°C as the highest temperature which can be envisaged under normal working conditions and base their test temperatures on that figure. Recent developments in transformer design both in this country and in America suggest that, by the use of inert-gas sealing, oil temperatures of about 130°C may be tolerated. Could s.r.b.p. bushings be used at these temperatures, and if so, should the specification not be suitably extended? Using the authors' formula relating temperature and power factor, this temperature would give an increase in power factor to the fourth power. Is the formula then applicable, and if not, what are its limits of application?

The use of alternating voltages for the discharge tests means, in general, that discharge will only occur for short periods on the voltage peak during each half-cycle. It would seem that in certain cases the use of a direct test voltage would have some advantage, in that the discharge would be continuous and therefore possibly easier to compare.

NORTHERN IRELAND CENTRE, AT BELFAST, 9TH FEBRUARY, 1954

Major E. N. Cunliffe: In order to interpret with any degree of accuracy the results of power-factor tests on site, it would appear to be desirable to have prior knowledge of the manner in which the power factor for a normal bushing insulator can be expected to vary with time in service. This is particularly so when the insulator is being tested at one voltage only, as in the on-load method. Although the authors have not included any power-factor/time curves in their paper, I feel that it would be both useful and instructive to have such information available.

Mr. J. M. W. McBride also contributed to the discussion at Belfast.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. H. Barker and **H. Davies** (*in reply*): Several speakers have mentioned service conditions which bushings may have to meet. The maximum operating temperature for s.r.b.p., raised by Messrs. McLean and Bratton, depends on the duration and frequency of the high-temperature conditions, but continuous operation up to 100°C would be permissible. Thermal decomposition of the cellulose is the limiting factor, and for this reason the use of silicone resin offers no improvement. Although, as

Mr. Coveney states, conductor temperatures can reach 85°C, 60°C is usually considered to be a reasonable average for the insulation material in a switchgear bushing.

We cannot agree that the possibility of over-voltages at alternator terminals, of the magnitude stated by Mr. Riach, justifies the 1 min over-voltage test.

We agree with Messrs. Torry and Fuller that the proximity of the surroundings of a bushing and other factors must be taken into account, and this is normally done by the manufacturer of complete equipment. Other speakers, notably Mr. Dalby, Dr. Maas and Mr. McCullagh, have raised interesting points on lightning protection, cracked porcelain, weathertightness, storage and handling, etc., and in general we agree with their remarks. They are, however, rather outside the scope of the paper, which has attempted to deal with those factors affecting the life and performance of bushings which can only be evaluated by testing of individual bushings and designs. Essential investigations into performance of materials and design features, mentioned by Dr. Maass, and of which Mr. Berry's tests on varnish finishes are examples, have of necessity been excluded from the paper. We have not experienced crazing of surface finishes giving rise to lodgment of carbon such as Mr. Shackleton describes, nor have we found anti-tracking finishes to be necessary for high-voltage bushings.

Mr. Rumfitt interprets our remarks in Section 4.2.2 to mean that we consider that moisture absorption is a thing of the past. We cannot see any justification for this interpretation. What we do say is that failures due to thermal instability are not experienced on modern insulators, and that one reason for this is improved moisture resistance. The relation between electric strength and moisture absorption is of secondary importance in this respect; more important is the relation between moisture absorption and electric losses.

We agree with Mr. Torry that the stress distribution may sometimes be improved by the water in the wet flashover test, but fail to see how this strengthens the case for retention of the test. We suspect Mr. Fuller's alternative test to be somewhat facetious, but a practicable test under polluted atmospheric conditions would certainly be desirable. In reply to Mr. Edwards, we see no reason why the 1 min routine over-voltage test should not be less than the wet-withstand voltage, as we consider that the 1 min overvoltage test is a quality-control test depending on the working voltage, and it bears no relation to the wet-withstand test.

All the test values in Table 1, and their comparison with existing 50 c/s test values, are based on the proposed international standard impulse levels. If suitable co-ordination and protection can reduce these levels, economy in bushing sizes would no doubt be feasible, as Mr. McNeill suggests. We would also suggest that many designs of bushings now in use have a generous margin over the present power-frequency oil-withstand values. In reply to Mr. Plumb, the $1\frac{1}{2}/40$ microsec wave is not less arduous for s.r.b.p. than the 1/50 microsec wave, and the limits specified for the latter also embrace the former. So far as we are aware there is no relationship between the American waveshape and their frequency of 60 c/s. In reply to Mr. Thomas, bushings designed to the impulse levels given in Table 1 should withstand the chopped-wave values, which are 15% higher.

We agree with Mr. Edwards that the 1 min over-voltage test cannot be considered to be a thermal-stability test, but we have suggested in the paper that one reason for its adoption was to eliminate bushings with patches of poor quality or pockets of moisture which would cause failure owing to thermal instability at lower voltages and longer times.

Dr. Walton suggests that a bushing may reach stability at a dangerously high temperature. Whilst this is theoretically possible it is most unlikely, since the electric-loss/temperature curve is so steep at such temperatures that the bushing would, in fact, not become stable. We cannot agree with Mr. Plumb that the thermal-stability test gives most information about a bushing, as the most important part of the voltage/time characteristic is that which embraces the working voltage, and in this range of stress, internal discharges are invariably the most important factor.

Several speakers have mentioned limits for power factor both in the factory and on site. These are determined so much by design, materials of manufacture, location and other conditions that no useful purpose would be served by attempting to lay down such limits. We agree with Mr. McCullagh that the specification of ionization points equivalent to the rated voltage is unnecessary and uneconomic.

In reply to Dr. Walton, power loss and capacitance are normally taken into consideration, and perhaps this could have been made clearer in the paper. It is unusual for capacitance to change noticeably during a power-factor/voltage test, but such a change could accompany a falling curve under certain conditions, e.g. a partially punctured layer which breaks down with an increase of voltage. In reply to Mr. Shackleton, a punctured layer is usually shown up by a power-factor/voltage test, and we are surprised that Mr. Jewell could not detect a punctured layer by this test, unless the equipment was somewhat insensitive. We are interested in Mr. Ashley's discharge and power-factor/voltage curves, which confirm our view that discharge tests give information additional to that provided by the power-factor/voltage test. It would have been interesting to see the results of discharge tests made on the bushings covered by Fig. C before they were put into service. Mr. Dalby's remarks on the gradual reduction in the amount of discharge in bushings in service are pertinent to this; whilst the effect has certainly occurred the reverse has also sometimes been the case. We also agree with Mr. Dalby that discharges are likely to produce radio and television interference.

We cannot understand why Mr. Rumfitt wishes to compare Figs. 5, 6 and 7, since they were intended to illustrate quite different things and do not necessarily bear any relation to each other.

With regard to site testing, a 10 kV Schering bridge will frequently give an indication of the deterioration of a condenser bushing for voltage ratings up to 33 kV and even higher, because faulty bushings often develop falling power-factor/voltage characteristics and/or exhibit higher capacitance, especially on the breakdown of a layer, and any deterioration by discharges usually causes such a partial breakdown at some stage. Absorption of moisture is usually shown by a high power factor. We agree with Mr. Edwards that more refined methods are required for modern insulators, but there is a danger of methods becoming too refined, with resultant difficulty in interpretation and possible rejection of sound bushings.

We agree with Mr. Drummond that it is desirable to apply reduced over-voltage tests to old insulators; the reduction depends on the particular circumstances. D.C. over-voltage tests of the magnitude mentioned by Mr. Shackleton should not be detrimental to bushings if they are clean and dry. With regard to insulation-resistance tests, we would refer Mr. Baker to Section 6.1.1 of the paper.

Several speakers have mentioned the need for site testing, and we agree with Mr. Berry that it depends on site conditions, etc., although our experience is that there is less need for frequent site testing with modern insulators. In reply to Mr. Campbell, we think that provision should be made on 275 and 380 kV bushings for testing on site, in view of the far-reaching consequences of breakdowns in such systems. Power-factor tests

would be the most useful; on-load testing could probably be applied, but it would depend on the particular circuit conditions and layout.

The method of on-load testing described by Messrs. Ashley and Berry is undoubtedly very simple and useful. It suffers from the disadvantage that there is no real standard by which the condition of the bushing can be assessed, and there may be considerable difficulty in interpreting the results. Mr. Connon overcomes this difficulty to some extent, but his method involves the use of another bridge and the isolation of at least one bushing per phase. This partially defeats the object of on-load testing. There may also be practical difficulties in a large station. In reply to Mr. Coveney, experience has shown that a voltage transformer without a tertiary winding can be used in the on-load testing method described in the paper.

In reply to Mr. Fuller, deterioration of the bushing shown in Fig. 9 would not have taken place if there had been no ionization at the conductor; and in reply to Mr. Coveney, the bushing shown in Fig. 11 was a circuit-breaker tank insulator.

With regard to Mr. Edwards's query on Figs. 3 and 4, the breakdown values given are instantaneous values.

We agree with Mr. Robertshaw that leakage testing by air is more sensitive, but oil testing has generally been quite adequate.

We agree with Mr. Watson that the curves shown in Figs. 1 and 2 are not completely representative at the lower spacings; in fact, it is doubtful whether any set of curves of this type would be. They were not meant to be applicable to all bushings, but were inserted to show, in a general way, differences which may be obtained on dry and wet flashover tests with impulse and power-frequency voltages.

DISCUSSION ON "TELEMETERING FOR SYSTEM OPERATION"*

(*Before the* MERSEY AND NORTH WALES CENTRE, *at* CHESTER, 16*th November*, 1953, *the* WESTERN CENTRE, *at* BRISTOL, 8*th March, and the* EAST MIDLAND CENTRE, *at* NOTTINGHAM, 23*rd November*, 1954.)

Mr. G. A. Burns (*at Chester*): I wonder whether the problem would have been tackled in the manner described in the paper had other sources of information been readily available, e.g. the photo-electric method of taking impulses from a watt-hour meter. With such an instrument and using the same pulse rate as is used for teleprinter signalling, the pulse-count method of telemetering could use a time-base of approximately 2 sec. This would mean that any reading occupying a channel would be correct every 2 sec, or (and this is frequently desirable) any selected reading would be available in a maximum time of 4 sec. Where several meters are required to be transmitted over one channel, up to ten meters could probably be transmitted in 20 sec.

It is appreciated that, with the form of metering demonstrated, the higher impulse rate available from the photo-electric transmitter would improve the response time, and it would be interesting to see what improvement could be anticipated.

Mr. E. A. Burton (*at Chester*): It is noted that extensive use is made of cold-cathode valves. In operation, the lower-voltage types require some light excitation. Does the type used in this equipment require such excitation? If so, I assume that without this feature these cold-cathode valves, and hence the equipment, would fail.

Mr. R. Colclough (*at Chester*): Although the equipment described in the paper has not been transmitting at a voice frequency, its equivalent, which the B.E.A. is to use, will transmit in the upper part of the speech band above 2 200 c/s. Would it not be possible to transmit the 120 c/s band of this equipment lower down the speech band, say around 1 600 or 800 c/s? I do not think that this would materially interfere with speech intelligibility, and it might then be possible to use lower-grade Post Office circuits, thus reducing rental costs.

What are the voltage limits of the cold-cathode tubes? We know from experience that maintenance of this type of equipment can be overlooked, and if the limits are close, a frequent check will have to be kept on the equipment.

Mr. W. L. Town (*at Chester*): It has occurred to me that there may be an alternative approach to this problem of transmitting information.

In system operation the control engineer wishes to have a continuous visual record of what is occurring in the remote metering stations, and in particular he is most interested in the rates of change recorded by them. To draw his attention to the latter, could there not be some form of indication on the meter, such as increased illumination of the dial, brought about by local circuits sensitive to rates of change, and transmitting a picture of the array of instruments by television?

In effect, the control engineer could view directly the situation existing in the remote stations and take action accordingly. I appreciate that the major objection to such a scheme would be the cost of the transmission cable, but the problems of converting the information to a suitable form for transmission do not arise, and furthermore, no time lags would be involved.

Mr. J. Garner (*at Bristol*): Is not the present method of indicating mains frequency from remote stations to the group control station more accurate than the "cup and bucket" method?

The impulse telemeter is dependent upon stabilized voltage supplies for its accuracy, and also thermionic-tube deterioration affects its calibration, whereas the existing system, having a voice-frequency tone modulated with the remote 50 c/s frequency, introduces no inaccuracies whatsoever.

Mr. T. E. Jackson (*at Bristol*): The earlier systems of meter indications, which might still be adequate for indications of load at a bulk supply point, are quite unsuitable for use on main transmission lines or for indicating the output from a generating station. In these cases, uninterrupted indications capable of following changes instantaneously are the ideal. Such indications have been provided by the photo-telemeter since 1936, but its application is restricted, since one frequency channel is required for each meter.

The authors have developed a method of remote metering which is a compromise. There is a slight delay in response, but the system lends itself to multiplex transmission of several meters over one frequency channel. At first sight, the coded system of transmission would appear to be wasteful in signal units compared with the cyclic distributor, and one wonders whether the latter, because of its greater traffic capacity, is to supersede the coded system. A comparison of the two schemes would be of interest. The transmission of direction by another system when the cyclic distributor is used seems undesirable, particularly under floating conditions.

* DUNN, R. H., and CHAMBERS, C. H.: Paper No. 1400 M, October, 1952 (see **100**, Part I, p. 39).

The bunching of pulses leaving a generator summator gives a wavering reading, but smoothing and the consequent delay in response to genuine changes seems a dubious solution to the problem.

Does the variable response, which is characteristic of the telemeter described in Section 4.2.2, discriminate between steady and changing conditions when the steady condition is a high reading, or only when it is floating?

The design of mains-driven power supplies on which remote metering is entirely dependent should be more than generous. Duplicate equipment with automatic change-over to cover failure of components seems essential. Ease of access with safety for maintenance, especially with the relatively high voltages used in electronics, must be provided without having to interrupt the indication service.

Remote meter indications can be no more accurate than the initiating measuring devices, i.e. voltage and current transformers, all of which have their own errors. I am sure that the authors will support a plea to meter users not to demand meaningless figures and graduations on magnified scales. If a meter has to be large, so that it can be read from a distance, the pointer should be correspondingly thick.

Mr. J. Smith (*at Bristol*): The main problem of the communication engineer has always been to convey the maximum intelligence over the smallest bandwidth. The cup-and-bucket meter, together with the multiplex distributor, helps to solve the problem. However, I should like to consider the reasons for limiting the number of meters dealt with by the distributor to ten.

First, the pulses are sent in cyclic order, i.e. their natural rate of sending is tampered with, and they can be transmitted only at a given instant during each scanning period irrespective of their actual time of origination. We are told that metering information of $66\frac{2}{3}$ impulses/min can be transmitted over the multiplex system at a speed of 50 bauds with adequate fidelity. However, if we were to increase the cyclic time by adding further meters the distortion would be correspondingly increased. It would seem that this problem is very similar to the bunched pulsing problem and can be solved by smoothing, which of course affects the response time. I appreciate that this distortion is not constant but will vary as the pulsing time falls in and out of phase with multiples of the cyclic time. However, can the authors give any figures for the worst possible conditions?

The next factor is the distortion caused by the cyclic times of the sender and receiver not being exactly the same. As the sender and receiver pulse together they will gradually get out of step, and a limit will be reached when the received pulses are no longer directed to the correct meters. It would appear that if this became a problem a further synchronizing pulse could be inserted in the train.

Next it seems that two successive "mark" signals cannot be effectively received on one meter, i.e. the "receive" circuit must be reset with a "space" signal before it can receive the next "mark." This would seem to limit the cyclic speed of the distributor and receiver to a minimum of twice the maximum pulsing speed of the meters, thus limiting the number of meters in the cycle. With signalling at 50 bauds and metering information transmitted at $66\frac{2}{3}$ impulses/min full scale, the number would be approximately 20. It therefore appears that response time, distortion and the number of meters per channel are all interdependent, and it would seem that in order to provide as many meters as possible they should only be as accurate as they need be, and have a response time as long as can be tolerated.

A problem also exists when the number of meters is small. At present the planner uses a 2-way relay distributor for two meters and two 2-way distributors on two channels for four meters, and for more than four meters a 10-way multiplex distributor. This leads to a desire, on the grounds of economy, to limit the number of meters to two or at the most four, or to fully equip a 10-way distributor. It would seem that a suitable compromise would be to provide multiplex distributors equipped only for the meters required at the outset but capable of being increased with the requirements of the system.

Compared with present-day practice 10 meters per channel seems generous indeed, but in future a line serving a super-Grid point could easily require 20 meters or even more.

Mr. H. H. Ledger (*at Nottingham*): Impulse metering of the type described by the author has been adopted by the B.E.A. as one of the features of its standardized supervisory equipment which is to be installed at all generating stations and supply points connected with the Grid system. It utilizes one or two super-a.f. channels on the private wire circuits used for supervisory and communication purposes. Each of these super-a.f. channels carries one of the multiplex distributors described in the paper and transmits ten metering terms.

In the East Midlands Division we are particularly fortunate in having one of the first prototype installations of standardized supervisory equipment in the country. It is installed at the Coventry generating station where it is connected with the Area control centre at Birmingham. Associated with this is a satellite installation at the smaller station at Warwick, which thus forms a typical group system as described in the paper. The following telemetering information is transmitted from Coventry to Birmingham:

Coventry total generated output in megawatts and megavars.
System frequency.
System voltage.
Feeder power flow on three feeders in megawatts.
Feeder power flow on one feeder in megavars.
Total generated output in megawatts and megavars of the Warwick station.

This system has now been in service for some four months.

It has been found that, owing to Post Office faults or disturbances on the line, the receiving end of the multiplex distributors may get out of synchronism. If, under these conditions, meters towards the end of the sequence are stationary and reproducing the multivibrator stop and start sequence of "mark" and "space," the decoding receiver may accept them as such and will not synchronize correctly. Have the authors any solution to this problem?

With regard to the elimination of electro-mechanical operation, the authors rightly claim that much electro-mechanical apparatus has been eliminated, but one of the key functions—that of the receiving relay for the multiplex distributor—is performed by a relay which may be operating almost continuously at speeds of up to 50 operations/sec. I am somewhat apprehensive about the life of that particular piece of apparatus, and I wonder whether an electronic relay has been considered for the purpose.

With regard to the response time, I would draw attention to the slower response of the total-generated-output meters. A limitation is also imposed on the total-generated-output initiating equipment which requires that there shall be a minimum interval of 0·7 sec between impulses. If these conditions are not observed the indicating meter may be affected by the random occurrence of the impulses.

In general, it would appear that the equipment is well suited to system-operation purposes where communication channels are limited to Post Office circuits, as occurs in most cases with the B.E.A. Where channel space is less restricted, as for instance with carrier circuits, it is possible to employ telemetering equipment having quicker response characteristics.

Messrs. R. H. Dunn and **C. H. Chambers** (*in reply*): We reply to the points raised by individual speakers under separate headings.

Mr. Burns.—There is no doubt that means for obtaining a selected reading in 4 sec will become available, but for continuous reading an alternative fast-counting and coding system giving ten readings in 20 or even 10 sec is not a sufficient improvement over the system described to justify the considerably increased complexity and cost involved. Faster response can be obtained only with increased bandwidth or more expensive equipment, and there are few cases where increased response justifies the cost.

Mr. Burton.—The tubes employed require some light to maintain operating conditions. A very wide range of illumination is acceptable, and an underrun lamp in the cubicle is normally adequate.

Mr. Colclough.—The signals can be transmitted anywhere in the speech band. It is a matter of accepted practice to use super-a.f. channels. The circuits as designed will operate over a voltage range of at least $\pm 20\%$.

Mr. Town.—A television system using the same standards as the public service and showing nine instruments on the screen would reproduce the instruments at a diameter of approximately 3 in. This is about the maximum capacity of the system, and its bandwidth requirements would indeed be expensive.

Mr. Garner.—With the present system there is inaccuracy in the indicating instrument. However, it uses a whole channel to itself and it is required to share such a channel with other services. Precision accuracy is not required.

Mr. Jackson.—The coded system handles eight to ten meters at $66\frac{2}{3}$ impulses/min on the average, and carries direction. The cyclic method therefore does not give much more capacity, and it introduces difficulties regarding synchronism. A modification of the circuit will enable directions to be carried in place of one meter. Delay in overcoming bunching represents another compromise. Existing metering equipment is used, thus saving considerable additional expense. The variable response occurs at all times but is most noticeable at low readings. We agree with the views on power supplies, which are a matter of sound engineering, and on accuracy. It is strange that so many engineers can fall into the trap of thinking that they are getting "something for nothing."

Mr. Smith.—The capacity of a cyclic distributor is stated correctly. The worst case is that of a slow beat frequency at a reading in the high part of the scale. The telemeter is more susceptible to a rhythmic error than a random one, and beat-frequency error sets the practical limit to the scanner capacity, as a compromise between capacity and error.

Mr. Ledger.—With regard to the possibility of false synchronizing in teleprinter signalling, the condition is accentuated by the manner in which it is being used. To overcome the difficulty we propose to introduce a suitable period of "mark" at regular intervals. With regard to the possibility of using an electronic relay in place of the electro-mechanical one, this has been given some thought, but with present techniques it is not an economic proposition. Further development may make it more attractive.

DISCUSSION ON "MAGNETIC MEASUREMENT OF MECHANICAL HARDNESS"*

Dr. W. N. Hindley (*communicated*): I wish to refer to the opening sentence of the Summary. Magnetic hardness may not be quite so new as the author would have us believe. The relationship between magnetic hardness (M.H.) and Vickers diamond hardness (H_D) has been known for many years. It was actively employed during the 1939–45 War for the inspection of armour-piercing bullet cores, and I built automatic magnetic-hardness testing machines to inspect and sort at the rate of 120 cores per minute on an accept/reject basis.

A machine would be adjusted so that the cores within the hardness range 850–920 H_D were accepted and those below 850 H_D and above 920 H_D were rejected. It should be mentioned that the cores (test pieces) were small steel samples with a constant hardness for a given sample throughout its mass.

A brief description of the principle is included in the Introduction to a paper on "Sources of Error in Diamond Pyramid Hardness Measurements on Hardened Steel."† A patent has been granted for improvements in H_D measurement using this principle.

Mr. D. Hadfield (*in reply*): I should like to make it quite clear that there was no intention of suggesting, in the Summary of the paper, that the subject of magnetic hardness was new. In fact, in the Introduction I did state that the subject was at least a century old. I do claim, however, that the method described in the paper is new and is quite different from any other methods which have been described. In point of fact, the original work was carried out as long ago as 1942 and was the subject of secret reports to the Ordnance Board dated 12th November, 1942, and 12th January, 1943. Unfortunately, it was not released before 1953 and for that reason was not published earlier.

Mr. Hindley's method does not depend on the permeability of the bullet cores but on the residual magnetization or remanent magnetism after saturating. After passing through the magnetizing field the working point would move from saturation in the first quadrant of the hysteresis loop, down to the demagnetization curve in the second quadrant, and to a value equal to the open-circuit working flux-density of the bullet core. The remanent magnetism was measured by dropping the cores through a search coil connected to a ballistic galvanometer whose deflection was proportional to the remanent flux, this in turn being proportional to the hardness. This method is satisfactory in this case since all the cores had the same composition and heat treatment, and thus the demagnetization curves were almost identical in disposition but would probably vary a little in fullness factor with hardness.

Unfortunately it was not possible to describe any other method of magnetic hardness measurement in the paper owing to space restriction.

* HADFIELD, D.: Paper No. 1596 M, January, 1954 (see 101, Part II, p. 529).
† *Journal of the Iron and Steel Institute*, 1945, 2, p. 245 P.

DISCUSSION ON
"RESISTANCE HEATING OF MILD-STEEL CONTAINERS AT POWER FREQUENCIES"*

SHEFFIELD SUB-CENTRE, 16TH DECEMBER, 1953

Mr. W. E. Burnand: With currents of the order of 800amp it needs no great length of cable to absorb 20 volts, leaving little for the pipe it is desired to heat. If the cable was of high resistance and was placed inside the lagging, the heat generated would add its share to heating the pipe instead of being wasted. It can also be an economy in the cable itself, which can be run at a high current density (with, of course, heat-resisting insulation) and an improved power factor.

The same principle is also applicable to the larger-diameter vessels (Fig. 2). Some 30 years ago I converted a steam-heated vessel 7ft in diameter and 5ft deep, and another 6ft 3in in diameter and 6ft 7in deep, in the manner shown in Fig. 2, with a high-resistance winding and provisions to take up expansion, thus utilizing both inductive and transmitted heating; the vessels were well lagged, and the installations were still highly satisfactory, with power factors of over 0·9.

I note with interest the wide applicability of the constant 1·57, although I would expect this not to hold for many of the alloy steels which are increasingly used.

The circuit in Fig. 5 referred to as "open delta" looks like a closed delta to me, with both ends of the pipe earthed. There seems a possibility of some circulating current (which, however, would be small) with a star-connected primary; has the author observed any, which might perhaps be noticed as a shrill note on local telephones?

Mr. J. R. Phillips: My department has undertaken a number of mains-frequency induction-heating problems in connection with preheating and stress-relieving for welding, the removal of shrink-fit couplings, heating for forging, etc. The largest jobs have been the local heating of boiler drums for welding, the work being carried out both on the shop floor and on drums erected in power stations. A section of a drum 4ft 6in in diameter and 4in thick erected some 80ft above the ground was heated, using a 70 volt supply from a 400kVA transformer to feed six turns of 1in cable. The initial power was 180kW with a current of 4kA. The section was heated to over 500°C in 4 hours and cooled slowly by switching the power on and off. A die block weighing 10 tons has also been successfully heated in a similar way. At the other end of the scale, a body 6in in diameter, formed from three drop-forgings welded together, is being softened prior to machining, on a production basis, using mains-frequency induction heating.

Another very useful application is the removal of couplings that have been shrunk on to shafts. A coupling of 35in outside diameter on a $23\frac{1}{2}$in shaft with a shrink fit of 0·036in had defied removal with gas heating. With seven turns of 1in cable from a 70 volt supply, giving an initial power of 124kW and 3660amp, the coupling was heated and removed in 25min. With this technique it is still necessary to use good pulling gear to start the coupling and remove it quickly before the heat has penetrated to the shaft. The essence of the job is getting the heat into the coupling quickly. A similar technique has been used to fit and remove stainless-steel sleeves on ships' propeller shafts.

A further application is the preheating of billets, which are subsequently heated to forging temperature by 1500c/s induction. In one case a coil about 80in long is used to put 180kW at mains frequency into billets of $3\frac{1}{2}$in square section. The total output of the heater is 2 tons an hour at 1200° C. This arrangement reduces the capital cost of equipment of this type.

Mr. R. Green: The expression given for power dissipation in pipes includes all the physical dimensions except the wall thickness, since it is assumed that the skin effect severely limits the cross-section available for conduction. I suggest, however, that the combination of high temperature, heavy current and small tube diameter can increase the penetration depth beyond the assumed 20–30 mils. An expression for the penetration depth is given in Section 4.1. No units are disclosed, however, and I suggest that when using ohm-centimetre units a factor of 10^9 should be included to make the expression read

$$\text{Penetration} = \frac{1}{2\pi}\sqrt{\frac{\rho 10^9}{\mu f}} \text{ centimetres}$$

where f is in cycles per second.

Dr. T. H. Barton: Table 3 shows that the skin depth is of the order of 0·025in, so that vessels having a wall thickness greater than, say, 0·1in and a radius of curvature greater than, say, 1in are, so far as such a thin skin is concerned, close approximations to a semi-infinite conductor having one plane surface. Hence the formula for the latter will be applicable.

I am surprised that the induction heating of the bottom of vessels by the use of pancake coils is found to be so inefficient. The only difference between this case and the type of induction heating described in the paper appears to be that in the latter case the induced current sheet is cylindrical, while in the former it is circular. A wide spacing between the inducing coil and the vessel will adversely affect the power factor, and I wonder whether the pancake-coil heating was tried with abnormally thick thermal insulation.

Dr. D. Harrison: The index 1·57, which is the power of I given in the author's law, is almost exactly $\pi/2$, and it is interesting to speculate whether this has any significance, or whether it is a mere coincidence. It would be of great value and interest if tests were carried out on a wide variety of pipes and vessels, of widely different magnetic materials, so as to determine whether or not the law is obeyed, because if it is found to be valid over the widest range, it is possible that the index 1·57 has some significance.

The author has not mentioned the possibility of proximity effects when the heated pipe and the return conductor are close together, as is desirable to reduce stray fields and losses. For pipes of equal diameter, acting as go and return, with centre distance of $1\frac{1}{2}$ diameters, the increase of resistance may be of the order of 30%, and for a centre distance of 2 diameters this increase may be about 7%.

Where the materials inside the pipe or vessel demand the use of stainless steel or other poorly magnetic material, it may be practicable to use an outer shell of mild steel, so as to obtain the relatively high resistance required.

Mr. C. A. M. Thornton (*in reply*): It is necessary to avoid the fallacy that, by employing a return cable of higher resistance

* THORNTON, C. A M.: *Proceedings I.E.E.*, Paper No. 1230 U, April, 1952 (see 99, Part II, p. 85).

and using it as an ohmic heating cable in contact with the pipe under the lagging, considerable improvement in efficiency is possible. Without recourse to this expedient the efficiency should be not less than 95%, so there is little margin for improvement. It is possible to arrange for the heating to be divided in any desired proportion between conductive and "heating element" heating, but the lower the proportion of conductive heating the slower the response to changes of control. For this reason we generally prefer to make the proportion of conductive heating a maximum, even at the expense of power factor. We also prefer to have the return cable accessible for maintenance.

We have always loosely described a pipe connected as shown in Fig. 5 as "open delta," although both ends are earthed, to distinguish it from the case in which the ends of the pipe are connected by a cable. Any earth circulating current there may be has never produced audible telephone interference, and a very large number of telephones are installed in the vicinity.

The removal of shrunk-on components is often much easier with induction heating, and if there is still any difficulty the application of solid carbon dioxide to the shaft may further assist removal.

The equivalent "skin" thicknesses given in Table 3 are calculated from the measured ratio of a.c./d.c. resistance and the measured wall thickness of the pipe. They are not assumed values. The formula in Section 4.1 is quoted from Reference 4 which, being a mathematical book, employs absolute units.

Mr. Green is correct in saying that temperature and current affect "skin" thickness, the former through its effect on resistivity and the latter through its effect on permeability; however, I do not think that tube-diameter enters into it. As the current in the pipe or vessel alternates in value, so the skin to which the current is confined pulsates in thickness. The equivalent skin thickness is the virtual value of this pulsating quantity.

It is an unfortunate weakness of some mathematical books on magnetism that they postulate non-existent material, namely material with a constant permeability appreciably different from unity. They do not say enough about how to deal with practical magnetic material, which always has extremely variable permeability. The gradual building up of contact resistance in contacts carrying heavy current for long periods is a familiar phenomenon, but in our conductive heating work special care has always been taken to avoid it. Silver plating or cladding at the contact faces is generally the simplest solution, and in switches and circuit-breakers without silver contacts occasional opening and closing to wipe away the oxide film.

Pancake-coil heating has never been tried with abnormally thick thermal insulation, but our desire to have the coil accessible with normally thick thermal insulation makes the coupling between coil and vessel bottom too weak to be effective. I do not think that there is any significance in the approximate equality between the index $1\cdot57$ and $\pi/2$, but there may well be a significance in the similarity between this law and that of Steinmetz, that the hysteretic loss varies as the $1\cdot6$th power of the flux density, and this in spite of the fact that our hysteretic loss is only a small percentage of the whole loss (see Table 3).

I have calculated the corresponding indices from tests on a commercial nickel pipe at various temperatures, with the following results:

Pipe temperature, °C	20	150	250	350
Value of n in formula $p = Ci^n$ in Fig. 6	$1\cdot58$	$1\cdot64$	$1\cdot62$	$1\cdot92$

The nickel passes through its Curie point in the neighbourhood of 360° C, as a result of which the value of n rapidly changes to 2 as the temperature is raised in the neighbourhood of 360° C.

Unfortunately the Curie point of nickel is thought to be sensitive to the composition of the nickel, which makes conductive heating of nickel pipe difficult to estimate correctly at temperatures above 300° C.

I agree that proximity effects have been neglected because we have never found our estimates to be vitiated by them; but they do exist, and by increasing the a.c. resistance of the pipe make it easier to get the required heat into the pipe.

DISCUSSION ON
"THE ROYAL FESTIVAL HALL: ELECTRICAL INSTALLATION"*

(*Before the* NORTH MIDLAND UTILIZATION GROUP, *at* LEEDS, 19*th January, the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, *at* BIRMINGHAM, 8*th February, and the* SOUTH-WESTERN SUB-CENTRE, *at* TORQUAY, 7*th April*, 1954.)

Mr. S. Addison (*at Leeds*): The author has shown us that in the Royal Festival Hall we have the product of the complete co-operation between the architect, the lighting engineer and his research workers, and the installation engineer, who has made everything work so successfully and safely.

The whole theme of the lighting has been to employ light sources without any glare sources, and the team of craftsmen are to be complimented on the excellent results produced.

I noticed that when following the author from the entrance, the sequence of rooms was:

Entrance lobby.
Main cloak room.†
Sunken foyer.
Main foyer.

and that we passed through varying levels of illumination, namely:

	8 lumens/ft²
	4 lumens/ft²
then to	50 lumens/ft²
and then down to	10/12 lumens/ft²

The increase in value from 4 to 50 is very great, but the eyes then having become "light adapted" have to adapt themselves in reverse to 10/12 lumens/ft², which is exceedingly difficult for elderly people. There must be some excellent reason why this high value was chosen, and possibly there is a gradual increase from the low to the high values. I should like the author to express his views on these differences in values, and to say what colour of tubes was used?

Another problem which rather puzzles me is why all the hot-cathode light sources in the building are 4 ft 40-watt tubes. Was

* HUNTER, J. G.: Paper No. 1412 U, December, 1952 (see 100, Part II, p. 69).
† Where additional illumination has been provided over the counter, which is very desirable.

there some particular reason why this type was preferred to the 5 ft 80-watt, which is generally considered a better commercial proposition?

In the auditorium, I was very pleased to see that incandescent lamps provided the main general lighting, since I am not entirely satisfied that it is correct to use near-white fluorescent sources with pinkish colours for interiors such as this. The social effect can be better obtained and controlled by the colour of the decorations or by the decorative lighting.

The designers are to be congratulated on the planning of the ceiling cove lighting, and for their choice of cold-cathode sources. I should like to know the colours of the tubes and of the coves.

The siting and concealing of the stage and orchestra sources calls for particular praise, but I hardly agree with the unique but costly method of changing lamps for those of a higher rated voltage in order to produce lower values in illumination. It is certainly desirable to avoid running the lamps in check for long periods in order to save wear and tear of the dimmers, but to underrun incandescent lamps not only reduces their efficiency in lumens per watt, incurring electricity wastage, but also seriously alters the colour of the light. I feel that it would be better to install more sources, possibly of a lower capacity, and control the amount of illumination desired by switches and dimming. There may possibly be complications and difficulties to balance the dimmer circuits with this alternative arrangement.

No reference has been made to the use of footlights, which I believe to be very desirable for ballet, and essential for soloists, but perhaps this equipment is included in the temporary and special effects.

Mr. J. R. Hanchett (*at Leeds*): The author states that the v.r. cables were installed in screwed conduits for lighting and power wiring, but that p.v.c. cables were used for signalling, cueing and sound-amplification circuits. I wonder why the difference was made; if the author was carrying out the installation to-day would he use p.v.c. entirely, since this material is cheaper and easier to pull into the conduits, as well as having a longer life.

The sub-main cables for power and lighting in vertical cable-runs were of the drained-cable type in order to minimize the risk of oil pressure-heads at low-level sealing chambers. I wonder why the author preferred this type to the pre-impregnated cable, since the latter would have been equally satisfactory.

In the sunken foyer the lighting is by 40-watt 4 ft fluorescent tubes, and I should be interested to know whether the control gear is of the instant-start type, and if so why it was preferred to the striker-switch variety; and if it is of the instant-start type is it one which requires the use of special lamps with an earthing strip, and has a lower light output?

Mr. N. S. Sellers (*at Leeds*): On the question of deterioration of h.r.c. fuses, I seem to recollect a statement in the technical Press to the effect that some 900 h.r.c. fuses have been replaced since the Royal Festival Hall was opened.

This figure seems incredibly high in view of the fact that the building has not yet been completed three years, and the deterioration of the installation cannot therefore be put forward as an excuse.

I should like the author's views on the use of miniature circuit-breakers in place of h.r.c. fuses, and would be interested to know whether in the light of experience, he would install miniature circuit-breakers if he were planning the installation at the present time.

Mr. G. E. McLean (*at Birmingham*): Could the author inform us why lead-acid batteries were chosen for the secondary lighting installation, and whether any consideration was given to the installation of a nickel-cadmium-alkaline battery? My own preference is for the lead-acid battery in glass containers, since one can so readily see the condition of the plates and can also assess the possible further life of such batteries much more easily than with metal-cased alkaline batteries.

Has it been found that the floating-battery system has caused more wear and tear on batteries owing to the difficulty of maintaining the rectifier output so as to balance exactly the fluctuating load of the secondary lighting installation, as compared with the trickle-charged battery system with the drop-out contactor change-over to the battery in case of failure of the mains supply? As the battery has now been installed some years, is there yet any appreciable deposition of sediment in the cells?

What type of high-voltage cable was used for the cold-cathode lighting installation, and were any special precautions taken as regards possible fire risks due to breakdown of insulation of cables or transformers, especially where such equipment is in close proximity to, say, wood-framed fibrous plaster mouldings?

It is noted that steel trunking was used for all services in switchrooms and for large concentrations of circuit cables. Were circuit cables and main cables run in the same trunking? If this is so a fault on a small circuit-cable might easily cause serious damage to main cables.

Can any information be given concerning the performance of the heating and ventilating plant, particularly with regard to the maximum and minimum volumes of air for both intake and extract systems that could be dealt with by the equipment. What range of values in the volume of air per person per hour and what variation in the number of changes of air per hour are obtainable in the auditorium, meeting hall and restaurant?

Mr. R. A. Joseph (*at Birmingham*): The first and most important point in the planning of this installation was the close liaison between the architect, the electrical engineers and the heating engineers. I should be interested to know whether the electrical engineers were called in at an early enough stage really to affect the planning of the building, or whether they were called in after the overall design had been completed.

I note that no cutting of beams was permitted, and I should be interested to know whether, in practice, the pre-planning of the holes in the beams and walls worked out satisfactorily. I imagine there must have been some alterations in the layout of runs necessary at a later stage. Was any cutting permitted then, or were such cable runs taken over the beams?

The author states that on the heating and ventilating system, motors have rotor-resistance speed control for a 40% speed reduction: this system seems wasteful. I should have thought that, with the amount of speed control probably necessary, commutator motors would have been economically justified.

Double-pole 30 amp micro-gap switches were used on the lighting installation, connected as two separate switches. I should be glad to know why this arrangement was adopted in preference to the use of individual switches, which would obviously have given greater individual control.

I note that metal-armoured flexible cable was used to connect from the anticipated to the actual position of lighting points, and that these cables were run in the pre-cast ceiling. Were the final positions of the lighting points decided upon before the ceilings were finalized, or was the metal armoured flexible cable run on the surface, or was the concrete cut away for it? I shall be glad to know whether the method used was successful since it might well have wider applications.

I note that stage lighting was dimmed by means of resistors. I imagine that ballet performances, and to some extent concerts, would call for a considerable amount of dimming, so the use of resistors would appear to be wasteful. Was there any reason why thyratrons were not used?

I should be interested to hear how successful the aural cueing

has proved in practice. I have heard mixed reports on its use in other installations.

I note that the main power distribution consists of paper-insulated lead-sheathed cables. Was the use of solid busbars run round the building considered at all? I should have thought that such a system would have been particularly attractive where final details of load were not available until a fairly late stage. No mention is made of fire-protection barriers in the rising trunks. Can the author give details of what was used?

Mr. H. M. Fricke (*at Birmingham*): I should like to know what contribution is made to the heating of the building by the substantial lighting load, all of which is dissipated in heat.

Mr. H. B. Mellor (*at Birmingham*): My first comment is on the earth-electrode system. I note this comprises driven 2 in tubes coupled with horizontal copper-tape links buried in the foundation excavations. Could the author give us any earth-resistance test results on the driven electrodes and also on the horizontal tapes? I am trying to arrive at the comparative values of the two systems.

As to the lightning-conductor arrangements, I note from the paper that the down-lead tapes are soldered on to the copper roof. Is there any form of mechanical joint in addition to soldering?

A useful addition to the paper would be a line diagram of the main and sub-main distribution system. This would tie up the description of the cables and switchgear contained in the paper.

I was pleased to read that imagination had been used regarding the number of 13 amp socket-outlets wired on one circuit, particularly where it was known that diversity would be very high.

A previous speaker mentioned segregation of wiring in the trunking system. I presume that cables have been bound or labelled so that circuits can be easily traced.

An expression is used in several parts of the paper, namely "mirror-glass reflectors with 150-watt tungsten lamps." Does this mean a separate reflector system or is it the 150-watt internal-reflector type of lamp?

Are the cold-cathode tubes of standard length or "tailor made" to suit the building?

Mr. S. R. Spruce (*at Birmingham*): I notice that micro-gap switches are referred to, I should be glad if the author could tell us how these switches have behaved in service, if they have been perfectly satisfactory so far, and if to his knowledge, they have ever been closed on a fault with which, presumably, the h.r.c. fuses would have to deal.

Mr. A. R. Wade (*at Birmingham*): I should like to ask what relationship the actual running load experienced bears to the installed transformer capacity. Also, are the micro-gap switches used purely for sub-circuit switching or are they in addition used for isolation purposes when repairs are being carried out to the lighting installation?

Has the author found that the 13 amp plugs and socket-outlets do in fact carry the full 3 kW load quite satisfactorily?

Are the primary and secondary lighting systems run as completely separate installations?

Mr. H. J. Gibson (*at Birmingham*): Since the likelihood of lightning striking a conducting surface covering the top of a building shaped like an umbrella is remote, but sharp corners or points encourage lightning, it would appear that, by providing lightning-conductor spikes around the lower and outer edge of the building, the effect of the domed metal roof of the central part of the building as a protection against direct lightning strikes is defeated. I should like to ask the author why supplementary lightning-conductor spikes were provided.

It is stated in the paper that a 1 500 kVA transformer is installed in the electricity supply substation, but the connected load at the moment is only 1 200 kVA, with a probable addition of 500 kVA for the extensions to the building, making a total of 1 700 kVA. I should like to know what the actual maximum demand has been, because it seems to me that a 1 500 kVA transformer to supply a connected load of 1 700 kVA, particularly of the kind in the Royal Festival Hall, is very large; I should have thought something about one-half the connected load would have been sufficient.

I presume the substation has been built at a distance away from the Hall because of possible fire risk. It would have been better at the centre of the load. Can the author say what earthing arrangements are made at the substation? Were the Electricity Board allowed to earth their l.v. and h.v. switchgear on to the earth provided for the equipment in the main building?

The arrangements of the main circuits and the sub-main circuits seem orthodox, and I wonder whether the possibility of ring mains, similar to the system frequently adopted on ships, was considered, or alternatively a busbar system. For example, it seems possible that a ring main could have been provided at each distribution level, or alternatively two vertical ring mains might have been practicable. The kind of building seems to lend itself to such an arrangement.

When I went to the Royal Festival Hall I noticed four microphones suspended from the roof. I should have thought that in a planned installation this would have been unnecessary and that all microphones could have been concealed. Can the author say why microphones of this type, which rather spoil the effect of the ceiling, are required?

I should like to refer to the lighting of the Hall, and in particular to what the author calls decorative lighting, by which I presume he means the side lighting such as that in the front of the boxes and on the walls. I do not consider that this is decorative in the sense that it has no utility value: it is supplementary to the top lighting, and I think it has the effect of preventing vertical surfaces being too much in shadow from the top lighting. I should like to ask the author whether the light from these side sources was taken into consideration when the illumination requirements of a particular area were considered.

Mr. T. D. G. Wintle (*at Birmingham*): With reference to the 13 amp socket-outlet, there is a little confusion in my mind as to the actual circuit arrangements here. The paper states that it was found economical to connect up to 6 sockets to a 7/·036 in circuit, and that ring circuiting was used in a few cases. Does that mean that more than 6 sockets were connected in some cases?

I should be glad if the author would tell us a little more about his experience with the fused plugs and sockets. I am interested to know whether they are of the round-pin type or the now standard flat-pin type.

I presume that the 30 amp double-pole micro-gap switch mentioned is the so-called micro-gap switch with approximately $\frac{1}{8}$ in gap. There is, to my knowledge, only one true micro-gap switch made.

As to the h.r.c. fuses, would the author tell us something about the category of fuse which it is found necessary to use in these boards?

Mr. J. B. Brockbank (*at Birmingham*): I understand that the heat-pump installation at the Festival Hall is being abandoned because it is too expensive to run. It is stated that it was designed as a base-load plant, to give about one-quarter of the estimated heat demand of the Hall, so that it could be run at its optimum efficiency, without expensive and elaborate controls. Unfortunately, it appears that the heat requirements were grossly over-estimated, so that the output of the heat pump is actually more than can ever be utilized. It therefore has to be run at outputs such that its efficiency is reduced, while constant manual control and supervision are necessary.

The unfortunate outcome of this experiment appears likely to be due to the factor so strongly emphasized by the author, namely lack of information in the design stages, and I wonder whether similar errors in estimating requirements have affected the electrical installation. In particular, one wonders whether the speed range provided on the heating and ventilating motors has proved sufficient.

I was interested also in the permanent wiring for B.B.C. requirements. A good many broadcasts have taken place from the Hall, and I presume that the permanent installation has been used for these, but I wonder whether it has been found necessary to add any temporary supplementary wiring. About 25 years ago I was responsible for the electrical installation in a technical college in a Midland town. This building was provided with a fairly large assembly hall from which it was thought that broadcasts might be made occasionally, and we took the trouble to provide permanent microphone wiring to a control point, with arrangements for suspending microphones at any required point in the hall. This was carried out to the requirements of the B.B.C. and was based generally on the newly completed installation in the concert hall at Broadcasting House. In fact, the installation has never been used. The first broadcast from the building took place comparatively recently, and complete temporary wiring was run for the purpose.

Mr. R. Paterson (*at Birmingham*): An earlier speaker mentioned that he could not understand why rotor-resistor control of speed had been adopted for the ventilating fan motors, and he suggested that a more efficient type of drive might have been adopted with advantage.

It is known that to achieve the specified 40% reduction the losses in the resistor will be 40% of the motor output, but it is not always appreciated that the power demand on fans varies nearly as the cube of the speed, so that at 60% of full speed the motor output is only about 25% of full-speed output, and the integrated losses in the resistor—amounting to about 40% of 25% of full-speed output—are not therefore so large as they might at first appear.

I have no doubt that in the planning stage, the author would assess the integrated losses arising from rotor-resistor control and equate them with the increased capital and maintenance expenditure for more complicated and more efficient types of drive.

Mr. F. H. Lealand (*at Birmingham*): I believe the Royal Festival Hall to be unique in its design and planning, but I certainly get the impression from the paper that the equipment in it was installed regardless of cost. I wonder whether the author would give us his views on the general economics when full lighting and heating loads are on, i.e. with a full building.

Mr. W. J. Guscott (*at Torquay*): I should like to know the method of metering adopted for the public supply to the Royal Festival Hall and the form of tariff and terms of supply.

I should also be interested to know whether the Electricity Board, in view of the importance of avoiding a failure of supply to a building accommodating so many people, had arranged for a duplicate service from a separate mains circuit, or whether the secondary-battery lighting would last long enough to clear the hall if necessary.

Mr. A. W. Allwood (*at Torquay*): It is noteworthy that the installation, although it reflects a considerable degree of credit on those responsible for its design and execution, is rather an outstanding example of orthodox practice than one which embodies any features of new or revolutionary character. In this it differs substantially from the other features of the Royal Festival Hall, such as its architecture, which is a complete break away from traditional design and has become a significant contribution in the world of contemporary architecture.

I note that the present installed loading is approximately 1 200 kW, but that this will be increased when the additional part of the Hall is completed, and that to supply this load the Electricity Board have installed a transformer capacity of 1 500 kVA. In view of the diversity likely to be experienced, this would seem to be somewhat excessive, and I should like to know whether the author has any details of maximum demands recorded during the period in which the Hall has been in use.

Mr. H. F. Truman also contributed to the discussion at Birmingham.

Mr. J. G. Hunter (*in reply*): In reply to Mr. Addison, the differences of illumination are an essential part of the scheme and serve to mould the architectural features by high-lighting certain areas. There is, however, no danger due to differences of intensity, since those of adjacent areas gradually merge into one another.

The hot-cathode tubes are a special colour, developed especially for this installation and known as "warm tint."

The 4 ft 40-watt hot-cathode unit was adopted of necessity to fit into the proportions of the architectural features.

Cold-cathode tubes are all warm white, and the reflecting surface of the ceiling is off white.

The work entailed in lamp changing is not so serious as it would appear, since adjustments are necessary to the angling and focus of the lanterns when changing over from concert to ballet or opera. The resultant alteration in the colour of the light is welcomed for orchestral purposes, and to meet this preference it would otherwise be necessary to employ a light straw-tinted filter.

Footlights are not provided as a permanent feature, but ample dimmer-controlled circuits are provided in "dip boxes" at the stage front. The decision on the type of lighting to be employed for a particular performance rests with the producer concerned, and the engineer can do no more than provide ample facilities. I am of the opinion that footlights should be used in certain cases.

In reply to Mr. Hanchett, I consider p.v.c. cables to be most suitable and should seriously contemplate their use to-day for all services.

Pre-impregnated paper cables were not available at the time specifications were prepared for the installation.

Instant-start gear was installed throughout the interior of the building and has proved most successful. I gave it preference on the score of lower cost initially and subsequently in view of absence of starter-switch troubles. Tubes with an earthing strip are not employed. It should be noted that instant-start gear is unsuitable for low temperatures, and, in view of this, starter-switch units were installed in all exposed positions such as entrance and porch lighting fittings.

In reply to Mr. Sellers, I am unaware of the Press statements to which he refers. The proportion of fuse replacements was at first large, owing to initial troubles to be found on any new installation of this size. Most of the replacements were due to failure of lamps which at that time were not provided with an internal fuse. Experience since gained leads me to the conclusion that the cost of miniature circuit-breakers would not have been justified.

In reply to Mr. McLean, a lead-acid battery was installed for no other reason than that I share his preference for a cell in a glass container, enabling its condition to be observed. The battery is in first-class condition, having a maximum depth of deposit of under $\frac{1}{4}$ in in four years. It suffers practically no wear and tear, since the rectifier output is automatically adjusted to the load, the regulation being by means of saturable-choke control having its d.c. winding in series with the secondary lighting load.

The high-voltage cables are 6 000 volt $1/\cdot083$ in single-core

tape-covered ozone-resisting vulcanized-rubber-insulated (120 mil lead-covered neon-sign cable), reference 65121/A, to B.S. 559. The electrical protection is in the form of h.r.c. fuses on the primary side, and all transformers are steel clad.

Main and sub-main cables were not installed in trunking containing sub-circuit wiring.

The capacities of the ventilating plants are as follows:

Auditorium.

Air supply (maximum)	80 000 ft³/min.
Air extracted (maximum)	60 000 ft³/min.
Air supply (minimum)	53 000 ft³/min.
Volume of air per person	1 250 ft³/hour.
Number of air changes at maximum output	5 changes per hour.
Number of air changes at minimum output	3·3 changes per hour.

Restaurant.

Ratio of air change	as for auditorium.

Meeting Hall.

Ratio of air change (at maximum)	10 changes per hour.
Ratio of air change (at minimum)	6·6 changes per hour.

In reply to Mr. Joseph, this job was one of the examples of good team work in which the engineers were consulted through all the steps of the planning and design, and in all but a few exceptions a complete agreement or a suitable compromise was reached with the architect.

A combination of pre-planning and early site supervision resulted in sufficient cable holes being provided. In general, the prearranged routes were adhered to, the variations being in the number and sizes of cables. I would emphasize, however, that such a result could not have been achieved without early and constant site supervision from the time the foundations were laid and the first earthing electrodes were driven.

The question of economic speed control was carefully considered, and it was decided that commutator motors were not justified, since the plant is usually run under optimum conditions and speed variation is, in practice, seldom used. In addition it must be remembered that, as the power required to drive a centrifugal fan varies as the cube of the speed, control by rotor resistance is not nearly so wasteful as it would at first appear.

Twin single-pole micro-gap switches are employed only on very large areas of lighting where a greater degree of individual control is important. It has the chief merit of economy in cost and space.

Metal-armoured flexible cables were employed in suspended ceilings to bridge the gap between the approximate positions of the outlets on the conduit system and the actual position of the lighting point in the pre-cast plaster ceiling which was later erected. In all such cases the metal-armoured flexible was installed after the pre-cast plaster work, the holes for the lighting units being sufficiently large for this purpose. This is most important, since one must have access for subsequent maintenance. All the metal-armoured cables are short and hang freely from the points on the concrete ceiling to the false plaster ceiling below.

I consider resistor dimming in this type of hall to be justified, since the duration of dimming, even for ballet, is relatively short. Resistor dimming is the only system showing no loss when the light is fully on or off, whilst thyratrons have a steady and considerable loss in the form of heater load whatever the demand on dimming.

The aural cueing has proved in practice so successful that the visual system is seldom if ever used, and I should hesitate to include visual cueing in future schemes. Aural cueing is so much more flexible and caters for changes in lighting plot, and corrections, abusive or otherwise are possible if the cue has been misinterpreted.

A busbar system was considered but found to be unsuitable for a number of reasons, the foremost being the need to meter the various sections of the building at the main switch-rooms. Fire barriers have been installed in all steel cable trunks at positions where they pass from one room or section of the building to another in addition to those at intervals in long lengths. This applies to sub-circuit cables only, since rising mains are either of the paper-insulated lead-covered steel-wire-armoured type or vulcanized-rubber insulated and in conduit, and where they pass from floor to floor through ducts the holes and spare ways are sealed off with incombustible material.

In reply to Mr. Fricke, the heating and ventilating system was designed with due regard to the dissipation of heat from the lighting, and since the system is thermostatically controlled, the contribution from lighting and other sources is automatically taken into account.

In reply to Mr. Mellor, the average resistance of the electrode system to earth is of the order of 0·1 ohm. The down-lead tapes from the copper roof pass right over it and are soldered and riveted at intervals. The inclusion of a line diagram was considered but proved in practice to be so large and complicated as to be unintelligible when reduced to the proportions of an illustration suitable for publication.

Cables in trunking were not bound or labelled, since I do not consider this to be any more necessary than in the draw boxes of a conduit system. Wiring in a trunking system can be revealed throughout its length and cables easily identified.

For the auditorium lighting general-service-type 150-watt lamps installed in minor glass reflectors are used. Internally silvered lamps were considered, but since, at the time of planning, they were newly introduced and insufficient experience had been gained of their life and performance, it was decided to adhere to the present system, which has proved very satisfactory.

With very minor exceptions all cold-cathode tubes are standard 8 ft 6 in lengths.

Instant-start units are installed for all interior hot-cathode tubes.

In reply to Messrs. Spruce and Wade, the micro-gap switches have given excellent service, and if ever they have been closed on to faults, they do not appear to have suffered from it. In my opinion credit in this direction should be accorded to the speed of the h.r.c. fuse in clearing the fault.

The maximum demand known up to the present time is of the order of 550 kW; micro-gap switches are in all cases installed for sub-circuit switching of large areas of lighting; no trouble has been experienced over the carrying capacity of the 13 amp plugs and sockets; and primary and secondary systems of lighting are run as completely separate installations.

DIGESTS OF INSTITUTION MONOGRAPHS

LEAKAGE FLUX AND SURFACE POLARITY IN IRON RING STAMPINGS

621.318.1.042.2 : 621.3.013.5 Monograph No. 116

P. HAMMOND, M.A., Associate Member

(DIGEST *of a paper published in January,* 1955, *as an* INSTITUTION MONOGRAPH *and republished in March,* 1955, *in Part C of the* PROCEEDINGS.)

It is a very surprising fact that the flux distribution around an annular iron ring is substantially constant regardless of the disposition of the magnetizing winding. The problem raised by this constancy of flux is often dismissed by the statement that the iron conducts flux because of its high permeability. This is undoubtedly correct, but scarcely deserves to rank as an explanation, if by explanation is meant that anyone who knew that iron has a high permeability should have foreseen the result. The treatment in the paper is based on the discussion of the problem given by Moullin.* It is assumed that, in order for there to be a certain flux density B at a point in the iron, there will also have to be a magnetic force H at that point. The problem of flux propagation, therefore, becomes the problem of the propagation of magnetic force. If the contributions of pole strength within the material are neglected, it is clear that the surface polarity on the iron must provide the mechanism by which the iron can maintain a substantially constant magnetic force throughout a particular iron circuit. If there is to be surface polarity on the iron, there will also be flux emerging from the iron. This flux is commonly called leakage flux and is often regarded as an imperfection in the design of the apparatus. But if we consider an iron-cored transformer in which the primary and secondary windings are wound on different portions of the core, it follows that it is the leakage flux that gives rise to the mutual flux. So far from being an imperfection in the design, the leakage flux is merely a manifestation of the surface polarity by which the iron maintains a constant mutual flux around the core. Without leakage flux there would be hardly any mutual flux in such a transformer. If the permeability of the iron is very large, a small surface polarity will be sufficient to maintain the flux constant around the iron. The fractional value of leakage flux will therefore tend to zero when the permeability tends to infinity, but it is clear that the absolute value of the leakage flux will not tend to zero. The problem should be considered with reference to Fig. 1.

In order to test the foregoing hypothesis, it was decided to derive a mathematical solution for the leakage flux in a certain problem and then to test the result experimentally. To simplify the mathematics it was decided to restrict the problem to two dimensions and to assume that the iron had constant permeability. The problem chosen was that of an infinitely long cylinder magnetized by a single current loop (see Figs. 2 and 3). The leakage flux was defined as the difference between the fluxes crossing sections A and B of the cylinder, respectively. The ratio of the fluxes at A and B was calculated to be

$$\frac{\Phi_A}{\Phi_B} = \frac{\mu \log \frac{a}{b} - 2 \log \left(1 - \frac{c}{b}\right) - 2 \log \left(1 - \frac{a}{d}\right)}{\mu \log \frac{a}{b} - 2 \log \left(1 + \frac{c}{b}\right) - 2 \log \left(1 + \frac{a}{d}\right)}$$

* MOULLIN, E. B.: "Principles of Electromagnetism" (Oxford University Press), Third edition, pp. 164–168.

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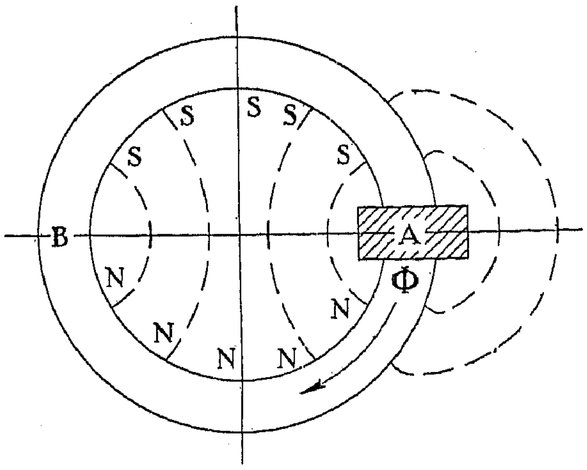

Fig. 1

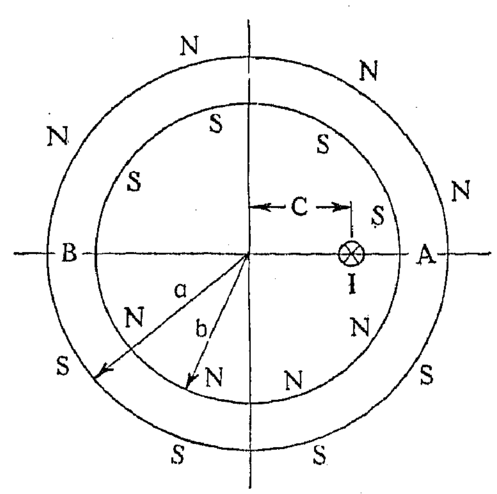

Fig. 2

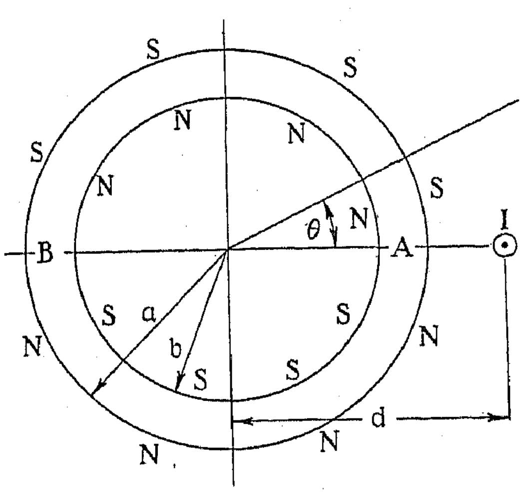

Fig. 3

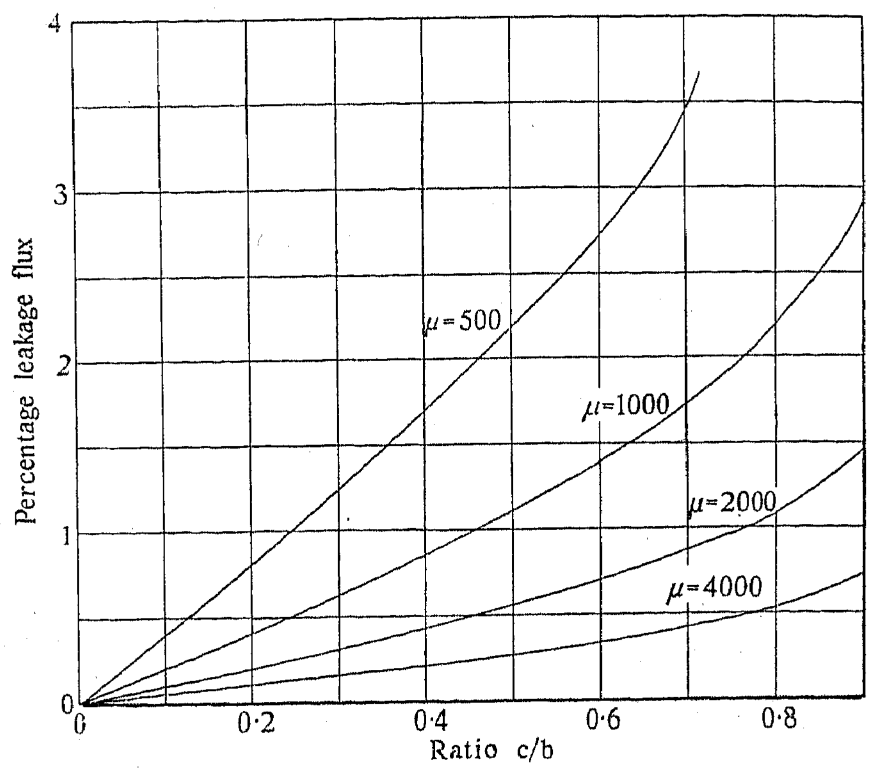

Fig. 4.—Theoretical leakage flux.

Fig. 4 shows the percentage leakage flux

$$\frac{\Phi_A - \Phi_B}{\Phi_A} \times 100$$

calculated for the case $a/b = 3/2$ and $c/b = a/d$ at different permeabilities and positions of the magnetizing loop. The curves show that the leakage flux increases considerably as the current is placed closer to the wall of the cylinder. A magnetizing winding consisting of a single loop is of course an extreme case, and in power transformers the leakage flux may be of little importance. But transformers are required in certain types of calculating machine, and in such applications it may be desirable to estimate the order of the discrepancy between voltage ratio and turns ratio.

It may well be doubted whether results based on the assumption of constant permeability of the material can be of any value when iron is used, especially if there is considerable saturation. The experimental results show that the results do, in fact, apply to iron of widely different permeabilities. The reason for this remarkable fact is that the actual value of the permeability does not matter greatly, so long as it is much larger than unity. In the paper it is shown that the boundary condition at the surface of the cylinder is

$$2\pi\sigma = \frac{\mu - 1}{\mu + 1} H_r$$

where σ is the local density of polarity and H_r is the magnetic force normal to the surface at the point considered. It will therefore be seen that the surface polarity is to a large extent independent of the permeability, and thus the absolute leakage flux is also independent of the permeability.

The experimental work was carried out on iron tubes of varying length built up from silicon-iron stampings lightly insulated on one side. The tubes were mounted, with their axes horizontal, on a slide which could be moved transversely to a long copper rod which carried the 50c/s magnetizing current. Search coils were wound on the tubes at opposite ends of a diameter and could be connected either in series or in opposition. An "integrating circuit" was used in order to obtain traces of flux density on an oscillograph. Fig. 5 shows some typical traces, and it will be seen that the leakage flux [Fig. 5(*b*)] is practically inde-

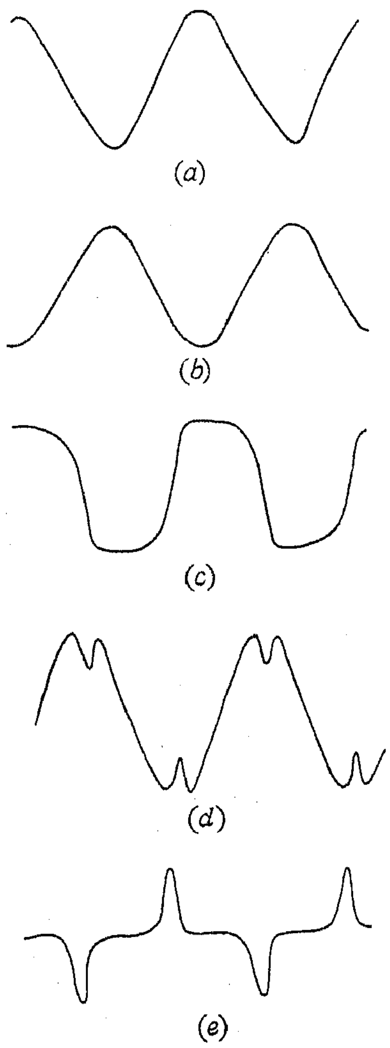

Fig. 5.—Waveforms.

(*a*) Current.
(*b*) Leakage flux.
(*c*) Mutual flux.
(*d*) "Leakage" voltage.
(*e*) "Mutual" voltage.

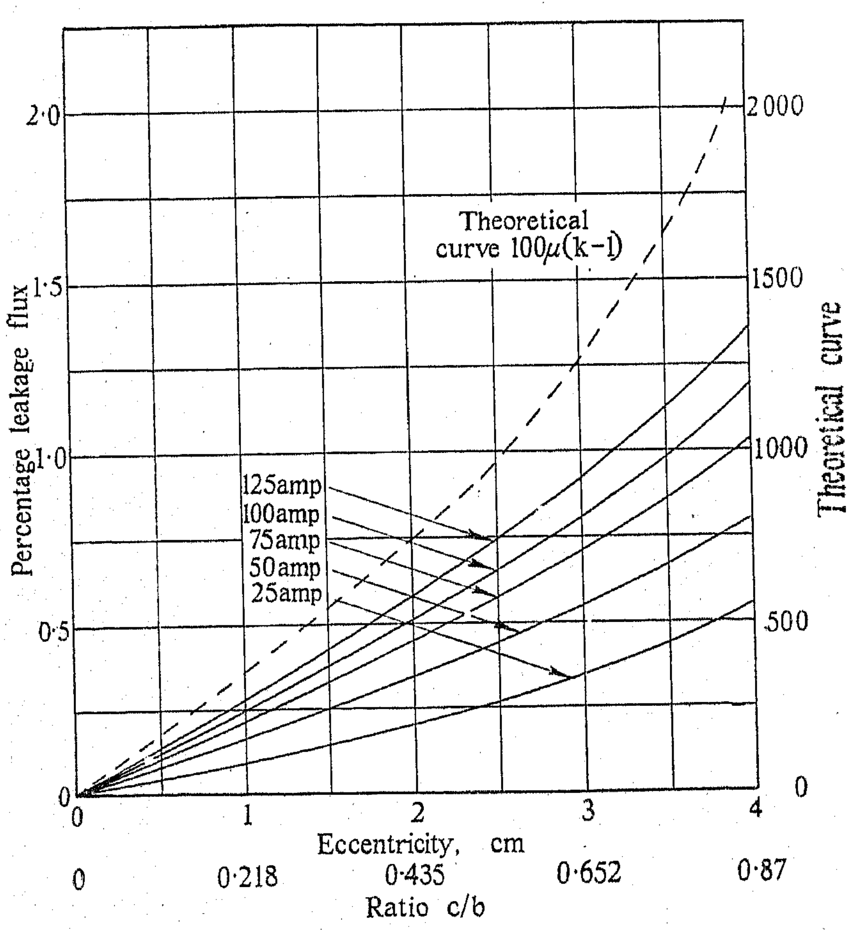

Fig. 6.—Percentage leakage flux in 35 cm tube.

pendent of the permeability, although there is considerable saturation [see Figs. 5(*c*) and 5(*e*)]. Fig. 6 shows the percentage leakage flux with different magnetizing currents and also the calculated curve for constant permeability. In Fig. 7 the shape

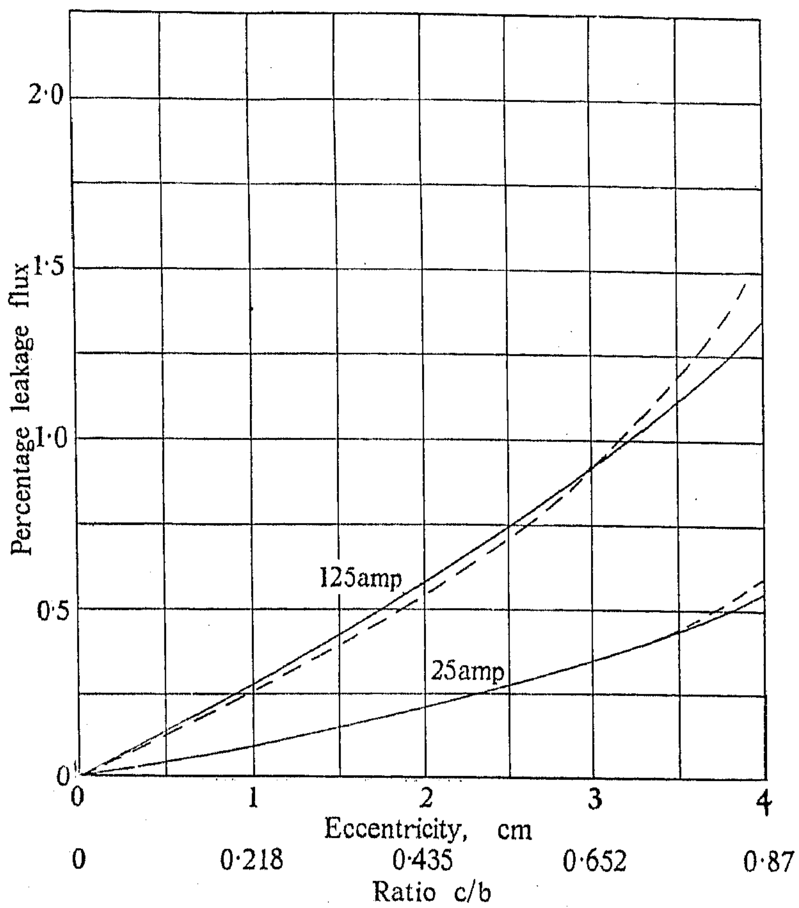

Fig. 7.—Comparison of shape of theoretical and experimental leakage-flux curves.

of the calculated and experimental leakage-flux curves is compared on the basis of choosing a value for the permeability which will make the theoretical and experimental curves coincide for the position of the magnetizing current when $c/b = 0\cdot65$ (see Fig. 2). The "equivalent permeabilities" obtained in this way are plotted in Fig. 8 for tubes of different lengths. The permeabilities obtained from a d.c. reversal curve are plotted in Fig. 8 for comparison. Some of the tubes had "guard rings"

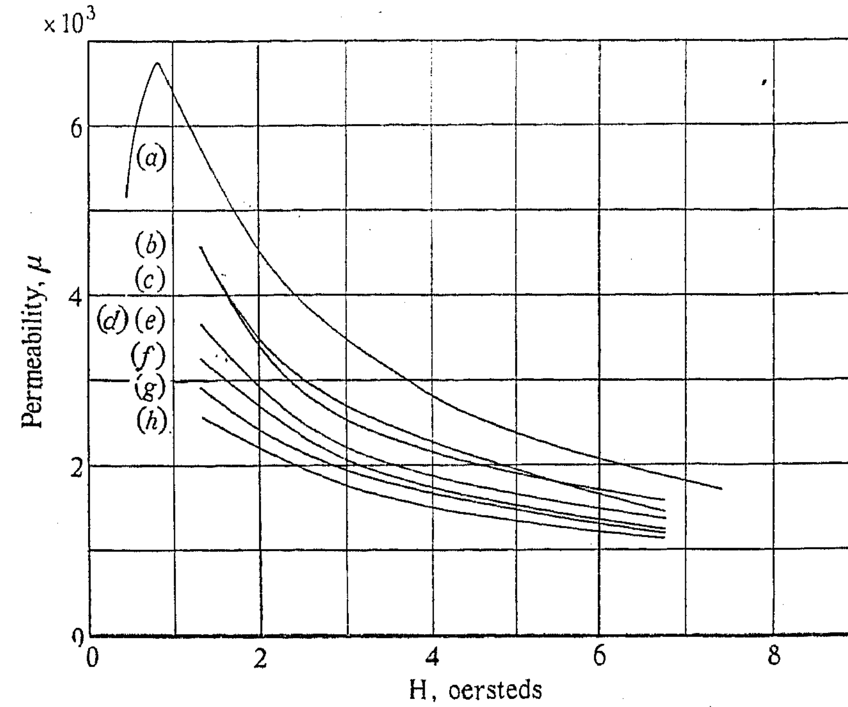

Fig. 8.—Comparison of equivalent permeabilities.

(*a*) D.C. reversal curve.
(*b*) 8·75 cm specimen packed both sides.
(*c*) 17·5 cm specimen packed both sides.
(*d*) 35 cm specimen.
(*e*) 17·5 cm specimen packed one side.
(*f*) 8·75 cm specimen packed one side.
(*g*) 17·5 cm specimen.
(*h*) 8·75 cm specimen.

in the form of further stampings placed at their ends in order to simulate more closely the case of an infinitely long tube. It is seen from Fig. 8 that there is good experimental agreement with the calculation, and that any discrepancy arises chiefly from the short length of the tubes.

It has been shown that surface polarity (or leakage flux) gives to the iron its remarkable property of being able to maintain a constant flux around an iron circuit magnetized by a concentrated coil. Good experimental agreement is obtained with calculations, even when these are based on the apparently drastic assumption of constant permeability of the iron. It therefore becomes possible to estimate the leakage flux in any particular set of iron-ring stampings and to estimate the order of the flux leakage in more complicated iron circuits.

THE TENSOR EQUATIONS OF ELECTRICAL MACHINES

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The recent increase in complexity of electrical power networks and control systems has led to the introduction of systematic methods of analysing the behaviour of networks and machines. There has been a trend towards the use of components of the currents, voltages and impedances of the system, which, while entirely fictitious, lead to elegant solutions. Examples are found in the use of symmetrical components for the study of unbalanced polyphase networks, or the two-reaction components in Park's theory of the synchronous machine.[18] In 1934 Kron, in America, developed a technique for dealing systematically with transformations of such systems of components.[1] He applied the transformation equations of tensor calculus to the analysis of electrical machinery (and networks) and by doing so developed a generalized theory covering most types of machines. The present paper brings together some of the scattered works of Kron and demonstrates the differences between tensor and non-tensor terms in machine equations.

The tensor technique is, briefly, as follows. The primitive machine shown in Fig. 1 is analysed using the electrical form of the dynamical equation of Lagrange in generalized co-ordinates.[5] In this machine the rotor is assumed to be smooth and to have on it a symmetrical two-phase winding sinusoidally distributed. The field is fixed in space and consists of the windings *ds* (direct-axis stator) and *qs* (quadrature-axis stator). The armature axes "a′" and "b′" are fixed on the armature and rotate with it. Three-phase machines may be analysed by resolving resultant

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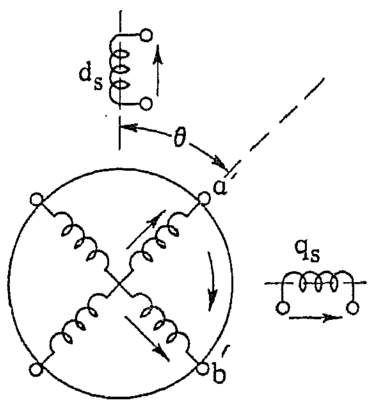

Fig. 1.—Primitive machine with axes fixed to windings.

current and flux vectors along similar axes. The equations of this machine are set up by inspection of the resistances and the self- and mutual-inductances of coupled coils of the system and by substitution in Lagrange's equation.

The self-inductance of phase "a′" of the machine shown in Fig. 1 may be written:[4]

$$L_A + L_B \cos 2\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $L_A = (L_{dr} + L_{qr})/2$
$L_B = (L_{dr} - L_{qr})/2$

L_{dr} and L_{qr} are the self-inductances of the rotor phase when it is in the direct and quadrature axes, respectively. The corresponding values of mutual inductance, rotor to stator, are M_d and M_q. θ is the angle of rotation of the rotor.

Lagrange's equation is written, in electrical form,[4]

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}^c}\right) - \frac{\partial T}{\partial x^c} + \frac{\partial F}{\partial \dot{x}^c} = f_c \quad . \quad . \quad . \quad . \quad (2)$$

The generalized variables x^c are the electrical charges in the circuits or the rotor angle of rotation θ. The quantities $\dot{x}^c$ therefore represent the currents i^c or angular velocity $d\theta/dt$. The index c is written as a superscript to conform with the notation of the tensor calculus.[19]

The stored magnetic energy T may be written down,[4] for the primitive machine shown in Fig. 1, as

$$\begin{aligned} T = {} & \tfrac{1}{2}(L_A + L_B \cos 2\theta)(i^{a'})^2 + \tfrac{1}{2}(L_A - L_B \cos 2\theta)(i^{b'})^2 \\ & + \tfrac{1}{2}L_{ds}(i^{ds})^2 - L_B \sin 2\theta(i^{a'}i^{b'}) + M_d \cos\theta(i^{ds}i^{a'}) \\ & - M_d \sin\theta(i^{ds}i^{b'}) + M_q \sin\theta(i^{qs}i^{b'}) + M_q \cos\theta(i^{qs}i^{b'}) \\ & + \tfrac{1}{2}L_{qs}(i^{qs})^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3) \end{aligned}$$

The dissipation function F is

$$F = \tfrac{1}{2}[R_{a'}(i^{a'})^2 + R_{b'}(i^{b'})^2 + R_{ds}(i^{ds})^2 + R_{qs}(i^{qs})^2] \quad . \quad (4)$$

Substituting eqns. (3) and (4) in eqn. (2), the complete set of equations for the machine may be written in matrix form as

The equation of Lagrange [eqn. (2)] may be written in a form such that transformation to new co-ordinates or components becomes a routine procedure. Thus the eqns. (5) for the primitive machine of Fig. 1 may be transformed to give those for the machine in Fig. 2, which has armature axes fixed relative to the field (i.e. a commutator type of machine). A wide range of machines may be analysed by comparing their circuits with

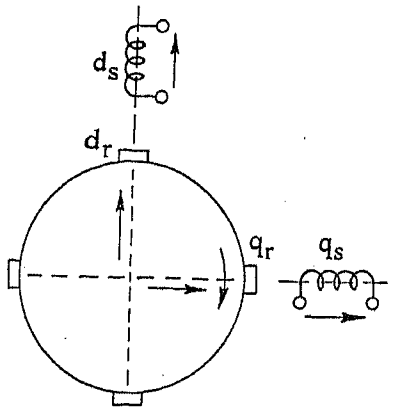

Fig. 2.—Primitive machine with stationary axes.

those of Figs. 1 and 2, since different interconnections of the coils of the latter two primitive forms give the circuits for many slip-ring and commutator machines. This aspect of the analysis has been extensively treated in References 2, 5, 8 and 10.

The present paper deals with another aspect of machine analysis that has been used more recently.[15,20,24] This consists of transformations among different reference frames of a given machine. A familiar example is that of the synchronous alternator which may be analysed either by setting up equations relative to three-phase armature terminals, or alternatively by using Park's equations, which contain quantities appearing in axes rotating with the field. The latter direct- and quadrature-axis quantities are, of course, fictitious, but they lead to simpler equations. It has been found, however,[20,21] that in hunting studies Park's equations based on axes fixed relative to the field are more complicated than those expressed along axes rotating freely at synchronous speed relative to the armature. The paper does not deal in detail with the equations of synchronous machines, but presents the concepts of transformations among the reference frames, using the tensor technique developed by Kron.

Tensors[19] are sets of quantities which are functions of a set of variables and are subject to certain laws of transformation when the variables are changed.

For example, differentials in two co-ordinate systems are connected by the relation

$$d\bar{x}^j = dx^i \frac{\partial \bar{x}^j}{\partial x^i} \quad \left\{ \begin{matrix} i = 1 \ldots n \\ j = 1 \ldots m \end{matrix} \right\} \quad . \quad . \quad . \quad (6)$$

$$\begin{array}{c} ds \\ a' \\ b' \\ qs \end{array} \begin{array}{|c|} \hline e_{ds} \\ \hline e_{a'} \\ \hline e_{b'} \\ \hline e_{qs} \\ \hline \end{array} = \begin{array}{c|c|c|c|c|} & ds & a' & b' & qs \\ \hline ds & R_{ds} + pL_{ds} & pM_d \cos\theta & -pM_d \sin\theta & \\ \hline a' & pM_d \cos\theta & R_{dr} + p(L_{dr}\cos^2\theta + L_{qr}\sin^2\theta) & p(L_{qr} - L_{dr})\sin\theta\cos\theta & pM_q \sin\theta \\ \hline b' & -pM_d \sin\theta & p(L_{qr} - L_{dr})\sin\theta\cos\theta & R_{qr} + p(L_{dr}\sin^2\theta + L_{qr}\cos^2\theta) & pM_q \cos\theta \\ \hline qs & & pM_q \sin\theta & pM_q \cos\theta & R_{qs} + pL_{qs} \\ \hline \end{array} \cdot \begin{array}{c} ds \\ a' \\ b' \\ qs \end{array} \begin{array}{|c|} \hline i^{ds} \\ \hline i^{a'} \\ \hline i^{b'} \\ \hline i^{qs} \\ \hline \end{array}$$

where $p \equiv d/dt$. . . . . . (5)

and the gradient of a scalar is given by

$$\text{grad } A = A_i = \frac{\partial A}{\partial x^i} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and in a new co-ordinate system

$$\bar{A}_j = A_i \frac{\partial x^i}{\partial \bar{x}^j} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The first example in eqn. (6) is that of a "contravariant" vector or tensor of the first order, and the indices are written as superscripts. The second example in eqns. (7) and (8) is that of a "covariant" vector, and the indices are written as subscripts.

The two forms of transformation may be written for (say) third-order tensors,

$$\textit{Contravariant:} \qquad \bar{u}^{abc} = u^{\alpha\beta\gamma} \frac{\partial \bar{x}^a}{\partial x^\alpha} \frac{\partial \bar{x}^b}{\partial x^\beta} \frac{\partial \bar{x}^c}{\partial x^\gamma} \quad . \quad . \quad (9)$$

$$\textit{Covariant:} \qquad \bar{v}_{jkm} = v_{\pi\ \kappa\mu} \frac{\partial x^\pi}{\partial \bar{x}^j} \frac{\partial x^\kappa}{\partial \bar{x}^k} \frac{\partial x^\mu}{\partial \bar{x}^m} \quad . \quad (10)$$

In machine studies the partial derivatives are usually denoted by the letter C. Thus a second-order contravariant tensor equation is written

$$\bar{u}^{ab} = u^{\alpha\beta} C^a_\alpha C^b_\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Each index occurring twice on one side is summed in every case and disappears, leaving a balance of indices on each side.

For electrical systems, Lagrange's equation in tensor form is written[1]

$$f_c = L_{ca}\ddot{x}^a + [ab,c]\dot{x}^a\dot{x}^b + R_{ca}\dot{x}^a \quad . \quad . \quad . \quad (12)$$

where f_c gives the applied voltages.
L_{ca} gives the self- and mutual-inductances of the windings.
R_{ca} gives the resistances of the windings.

and
$$[ab,c] = \frac{1}{2}\left(\frac{\partial L_{cb}}{\partial x^a} + \frac{\partial L_{ca}}{\partial x^b} - \frac{\partial L_{ab}}{\partial x^c}\right) \quad . \quad . \quad . \quad (13)$$

$\dot{x}^a$ gives the currents flowing in the various windings. Eqn. (12) as a whole is a tensor equation and transforms to new co-ordinates by

$$f_m = f_c C^c_m \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

and
$$f_m = L_{mk}\ddot{x}^k + [kn,m]\dot{x}^k\dot{x}^n + R_{mk}\dot{x}^k \quad . \quad . \quad . \quad (15)$$

where
$$L_{mk}\ddot{x}^k + [kn,m]\dot{x}^k\dot{x}^n + R_{mk}\dot{x}^k = (L_{ca}\ddot{x}^a + [ab,c]\dot{x}^a\dot{x}^b + R_{ca}\dot{x}^a)C^c_m \quad . \quad (16)$$

While the equation as a whole is a tensor equation, the term $[ab,c]$ is not by itself a tensor and transforms according to the law

$$[kn,m] = [ab,c]C^a_k C^b_n C^c_m + L_{ca}C^c_m \frac{\partial C^a_k}{\partial x^n} \quad . \quad . \quad (17)$$

The relationship among the axis currents of the machines of Figs. 1 and 2 is as follows:

$$\left.\begin{aligned} i^{ds} &= i^{ds} \\ i^{a'} &= i^{dr}\cos\theta + i^{qr}\sin\theta \\ i^{b'} &= -\,i^{dr}\sin\theta + i^{qr}\cos\theta \\ i^{qs} &= i^{qs} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (18)$$

or in index notation
$$i^c = i^m C^c_m \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where

$$C^c_m = \begin{array}{c|cccc} c \backslash m & ds & dr & qr & qs \\ \hline ds & 1 & & & \\ a' & & \cos\theta & \sin\theta & \\ b' & & -\sin\theta & \cos\theta & \\ qs & & & & 1 \end{array} \quad . \quad . \quad (20)$$

The set of eqns. (18) gives a relationship among the differentials of the variables (since $i^a = dx^a/dt$), and it is found that no relation between actual variables can be determined since the equations are non-integrable. The paper examines this relationship together with the modified form of Lagrange's equation required when this "non-holonomic" type of transformation arises.

The modified equation is that given by Boltzmann and Hamel,[1,6,13]

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}^c}\right) - \frac{\partial T}{\partial x^c} + \frac{\partial T}{\partial \dot{x}^d} C^k_c C^n_a \left(\frac{\partial C^d_k}{\partial x^n} - \frac{\partial C^d_n}{\partial x^k}\right)\dot{x}^a + \frac{\partial F}{\partial \dot{x}^c} = f_c \quad . \quad (21)$$

In tensor form this equation is written[6]

$$f_c = L_{ca}\frac{d^2x^a}{dt^2} + \Gamma_{ab,c}\frac{dx^a}{dt}\frac{dx^b}{dt} + R_{ca}\frac{dx^a}{dt} \quad . \quad . \quad (22)$$

where
$$\Gamma_{ab,c} = [ab,c] + \Omega_{cb,a} + \Omega_{ca,b} - \Omega_{ab,c} \quad . \quad . \quad (23)$$

and
$$\Omega_{ab,c} = \tfrac{1}{2}C^k_a C^n_b \left(\frac{\partial C^d_k}{\partial x^n} - \frac{\partial C^d_n}{\partial x^k}\right)L_{dc} \quad . \quad . \quad . \quad (24)$$

The paper examines in detail the nature and applications of the "non-holonomic" symbols $\Omega_{ab,c}$, etc.

The equation of the machine in Fig. 2 is written

$$e_m = R_{mk}i^k + L_{mk}pi^k + \Gamma_{kn,m}i^k i^n \quad . \quad . \quad . \quad (25)$$

The indices can take either the electrical part of the range of values, to give the voltage equation, or the mechanical part (denoted by the index s) to give the equation of torque.[2] This leads to the equations for the machine shown in Fig. 2. The electrical equation is

$$e_m = R_{mk}i^k + L_{mk}pi^k + 2\Omega_{ms,k}i^s i^k \quad . \quad . \quad . \quad (26)$$

$$R_{mk} = \begin{array}{c|cccc} m \backslash k & ds & dr & qr & qs \\ \hline ds & R_{ds} & & & \\ dr & & R_{dr} & & \\ qr & & & R_{qr} & \\ qs & & & & R_{qs} \end{array} \quad . \quad . \quad (27)$$

$$L_{mk} = \begin{array}{c|cccc} m \backslash k & ds & dr & qr & qs \\ \hline ds & L_{ds} & M_d & & \\ dr & M_d & L_{dr} & & \\ qr & & & L_{qr} & M_q \\ qs & & & M_q & L_{qs} \end{array} \quad . \quad . \quad (28)$$

$$2\Omega_{ms,k} = \begin{array}{c|cccc} m \backslash k & ds & dr & qr & qs \\ \hline ds & & & & \\ dr & & & L_{qr} & M_q \\ qr & -M_d & -L_{dr} & & \\ qs & & & & \end{array} \quad . \quad . \quad (29)$$

Thus eqn. (26) is expanded to

$$\begin{array}{c|c} m\backslash & \\ \hline ds & e_{ds} \\ dr & e_{dr} \\ qr & e_{qr} \\ qs & e_{qs} \end{array} = \begin{array}{c|cccc} m \backslash k & ds & dr & qr & qs \\ \hline ds & R_{ds} + L_{ds}p & M_dp & & \\ dr & M_dp & R_{dr} + L_{dr}p & L_{qr}p\theta & M_qp\theta \\ qr & -M_dp\theta & -L_{dr}p\theta & R_{qr} + L_{qr}p & M_qp \\ qs & & & M_qp & R_{qs} + L_{qs}p \end{array} \cdot \begin{array}{c|c} k\backslash & \\ \hline ds & i^{ds} \\ dr & i^{dr} \\ qr & i^{qr} \\ qs & i^{qs} \end{array} \quad . \quad . \quad . \quad . \quad (30)$$

The equation of torque is

$$f_s = R_{st}\frac{d\theta}{dt} + L_{st}\frac{d^2\theta}{dt^2} + 2\Omega_{sn,k}i^ki^n \quad . \quad . \quad . \quad (31)$$

where $$2\Omega_{sn,k} = -\text{ (matrix 29)} \quad . \quad . \quad . \quad . \quad (32)$$

In eqn. (26) the term $2\Omega_{ms,k}\, i^si^k$ gives the generated voltages, and in eqn. (31), $2\Omega_{sn,k}i^ki^n$ gives the generated torque.

Eqn. (26) may be written

$$e_m = R_{mk}i^k + L_{mk}pi^k + G_{mk}i^kp\theta \quad . \quad . \quad . \quad (33)$$

The equation of the machine shown in Fig. 3, with rotating axes is

$$e_\gamma = R_{\gamma\alpha}i^\alpha + L_{\gamma\alpha}pi^\alpha + \Gamma_{\alpha\beta,\gamma}i^\alpha i^\beta \quad . \quad . \quad . \quad (34)$$

where $$\Gamma_{\alpha\beta,\gamma} = [\alpha\beta,\gamma] + \Omega_{\gamma\beta,\alpha} + \Omega_{\gamma\alpha,\beta} - \Omega_{\alpha\beta,\gamma} \quad . \quad . \quad (35)$$

The matrix equation in this reference frame is examined in the paper. It may be obtained by transforming the equations of either the first or second primitive machine, and it leads to an equation of the form[8]

$$e_\gamma = R_{\gamma\alpha}i^\alpha + L_{\gamma\alpha}pi^\alpha + G_{\gamma\alpha}i^\alpha p\theta + V_{\gamma\alpha}i^\alpha p\theta_1 \quad . \quad (36)$$

The tensor and non-tensor properties of the terms of this equation are examined.

To demonstrate in a simple manner the application of the above methods of transformation of reference axes, the equations of an induction motor are examined. A three-phase motor has been analysed by Stanley[9] by resolving the three-phase quantities into equivalent two-phase axes which are relatively stationary on stator and rotor. The equations along these axes are:

$$\begin{array}{c|c} & \\ \hline ds & e_{ds} \\ dr & 0 \\ qr & 0 \\ qs & e_{qs} \end{array} = \begin{array}{c|cccc} & ds & dr & qr & qs \\ \hline ds & R_{ds} + L_{ds}p & Mp & & \\ dr & Mp & R_r + L_rp & L_rp\theta & Mp\theta \\ qr & -Mp\theta & -L_rp\theta & R_r + L_rp & Mp \\ qs & & & Mp & R_{qs} + L_{qs}p \end{array} \cdot \begin{array}{c|c} & \\ \hline ds & i^{ds} \\ dr & i^{dr} \\ qr & i^{qr} \\ qs & i^{qs} \end{array} \quad . \quad . \quad (37)$$

The steady-state equations for balanced conditions are found by putting $p = j\omega$. In the synchronous-machine equations of Park the rotating vector quantities (fluxes, currents, etc.) are constant under balanced steady-state conditions, and the corresponding equations are found by putting $p = 0$. This difference is one of reference frames. In Stanley's equations the reference axes are stationary and the flux rotates at synchronous speed, whereas in Park's two-reaction theory the reference axes rotate with the flux. When interconnected machines are being studied it is desirable that phenomena are related in the same reference frames.

The equations of the induction motor expressed along a

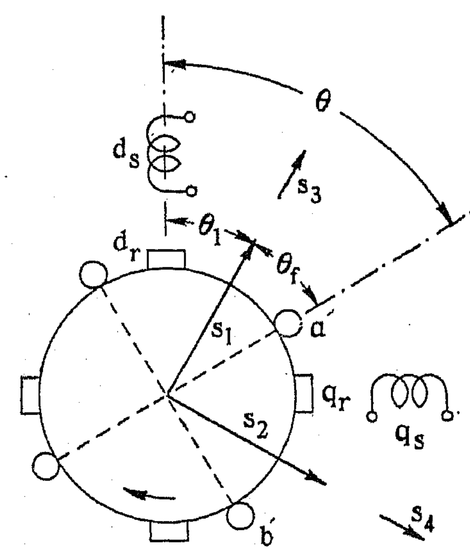

Fig. 3.—Primitive machine with axes rotating freely.

reference frame rotating with uniform angular velocity $p\theta_1$, are (see Fig. 3)

$$\begin{array}{c|c} S_3 & e_{S3} \\ S_1 & e_{S1} \\ S_2 & e_{S2} \\ S_4 & e_{S4} \end{array} = \begin{array}{c|cccc} & S_3 & S_1 & S_2 & S_4 \\ \hline S_3 & R_{ds}+L_{ds}p & Mp & -Mp\theta_1 & -L_{qs}p\theta_1 \\ S_1 & Mp & R_r+L_rp & -L_rp\theta_s & -Mp\theta_s \\ S_2 & Mp\theta_s & L_rp\theta_s & R_r+L_rp & Mp \\ S_4 & L_{ds}p\theta_1 & Mp\theta_1 & Mp & R_{qs}+L_{qs}p \end{array} \cdot \begin{array}{c|c} S_3 & i^{S3} \\ S_1 & i^{S1} \\ S_2 & i^{S2} \\ S_4 & i^{S4} \end{array} \quad (38)$$

(where $p\theta_s = p\theta_1 - p\theta$)

or $$e_\gamma = R_{\gamma\alpha}i^\alpha + L_{\gamma\alpha}pi^\alpha + G_{\gamma\alpha}i^\alpha p\theta + V_{\gamma\alpha}i^\alpha p\theta_1 \quad . \quad (39)$$

where

$$R_{\gamma\alpha} = \begin{array}{c|cccc} & S_3 & S_1 & S_2 & S_4 \\ \hline S_3 & R_{ds} & & & \\ S_1 & & R_r & & \\ S_2 & & & R_r & \\ S_4 & & & & R_{qs} \end{array} \quad . \quad . \quad (40)$$

$$L_{\gamma\alpha} = \begin{array}{c|cccc} & S_3 & S_1 & S_2 & S_4 \\ \hline S_3 & L_{ds} & M & & \\ S_1 & M & L_r & & \\ S_2 & & & L_r & M \\ S_4 & & & M & L_{qs} \end{array} \quad . \quad . \quad (41)$$

$$V_{\gamma\alpha} = \begin{array}{c|cccc} & S_3 & S_1 & S_2 & S_4 \\ \hline S_3 & & & -M & -L_{qs} \\ S_1 & & & -L_r & -M \\ S_2 & M & L_r & & \\ S_4 & L_{ds} & M & & \end{array} \quad . \quad . \quad (42)$$

or $$e_\gamma = R_{\gamma\alpha}i^\alpha + L_{\gamma\alpha}pi^\alpha + \rho_1 L_{\gamma\alpha}i^\alpha p\theta + \rho_2 L_{\gamma\alpha}i^\alpha p\theta_1 \quad . \quad (43)$$

where

$$\rho_1 = \begin{array}{c|cccc} & S_3 & S_1 & S_2 & S_4 \\ \hline S_3 & & & & \\ S_1 & & & -1 & \\ S_2 & & 1 & & \\ S_4 & & & & \end{array} \quad . \quad . \quad (44)$$

$$\rho_2 = \begin{array}{c|cccc} & S_3 & S_1 & S_2 & S_4 \\ \hline S_3 & & & & -1 \\ S_1 & & & -1 & \\ S_2 & & 1 & & \\ S_4 & 1 & & & \end{array} \quad . \quad . \quad (45)$$

In terms of flux vectors[15]

$$\boldsymbol{e} = \boldsymbol{Ri} + p\boldsymbol{\psi} + \boldsymbol{B}p\theta + \boldsymbol{\varphi}p\theta_1 \quad . \quad . \quad . \quad (46)$$

In this form the steady-state equations for a balanced symmetrical machine are obtained by putting $p = 0$ and using the relationships

$$i^{S4} = ji^{S3} \quad \text{and} \quad i^{S2} = ji^{S1} \quad . \quad . \quad . \quad . \quad (47)$$

and the operator p has the same significance under transient conditions as it has in the synchronous-machine equations of Park. Equations of torque and the invariance of power under the transformation are discussed.

Synchronous-machine equations of the form of eqns. (43) are discussed by Kron in Reference 15 and used in his hunting analysis in Reference 20.

The tensor method of electrical-machine analysis is systematic, and the equations are of a form that often leads to clearer concepts of the interactions of the currents and fluxes in the system.

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ALTERNATING VOLTAGE, DIRECT-VOLTAGE REGULATION DROP AND POWER FACTOR OF CONVERTOR STATIONS OPERATING ON A.C. SYSTEMS OF FINITE SHORT-CIRCUIT CAPACITY

621.311.44 : 621.3.015.1 : 621.3.018.14 Monograph No. 131 S

ERICH UHLMANN, Dr.-Ing.

(DIGEST *of a paper published as an* INSTITUTION MONOGRAPH *in May, 1955, and to be republished in Part C of the* PROCEEDINGS.)

In calculating the performance characteristics of a convertor station the assumption is generally made that the alternating voltage at the convertor station is sinusoidal, which, however, is not justifiable unless the short-circuit capacity of the a.c. system feeding the station is extremely large compared with the rating of the convertor itself. In the paper a method of calculating these characteristics without having to make the above assumption is developed, and the expressions obtained are referred to the r.m.s. value of the station voltage, where this will, in general, not be sinusoidal on account of the convertor loading. The results obtained by this method are being incorporated in a new document, "Recommendations for Mercury-Arc Convertors," which is to be published shortly by the International Electrotechnical Commission, and the purpose of the paper is to show the derivation of the formulae used to calculate the curves included in the new document.

For the purposes of calculation the a.c. system is replaced by an equivalent ideal generator, producing a sine-wave voltage at an imaginary feeding point, and delivering current to the convertor station via an equivalent lumped impedance representing that of the a.c. network plus that of the various generators feeding the system. A formula is then derived relating the r.m.s. value of the alternating voltage at the convertor station with that of the terminal voltage of the ideal generator. The results obtained are then used in the deduction of the additional direct-voltage regulation drop, due to the a.c. system, which is to be added to the direct-voltage regulation calculated in the normal way, i.e. with the assumption that the alternating voltage at the convertor station is sinusoidal. In this way the total direct-voltage regulation is obtained. A formula for the fundamental wave of the alternating voltage at the convertor station is also derived.

The second half of the paper deals with the question of power factors and displacement factors (power factor of the fundamental wave) of convertor stations. Formulae are derived in which these items are related to the r.m.s. value of the station voltage, taking into account the impedance of the a.c. system; and at the end of the paper approximate formulae are given which can be used to estimate the power factors and displacement factors in question to an accuracy of $\pm 0 \cdot 01$ for most practical cases. It is also shown that the power factors and displacement factors of convertor stations depend entirely on known plant and a.c. system data, and consequently that acceptance-test measurements of these items serve, in reality, no genuine purpose as they merely confirm this dependency.

Charts of curves are included throughout the paper which have been calculated from the various formulae over a range covering most practical cases.

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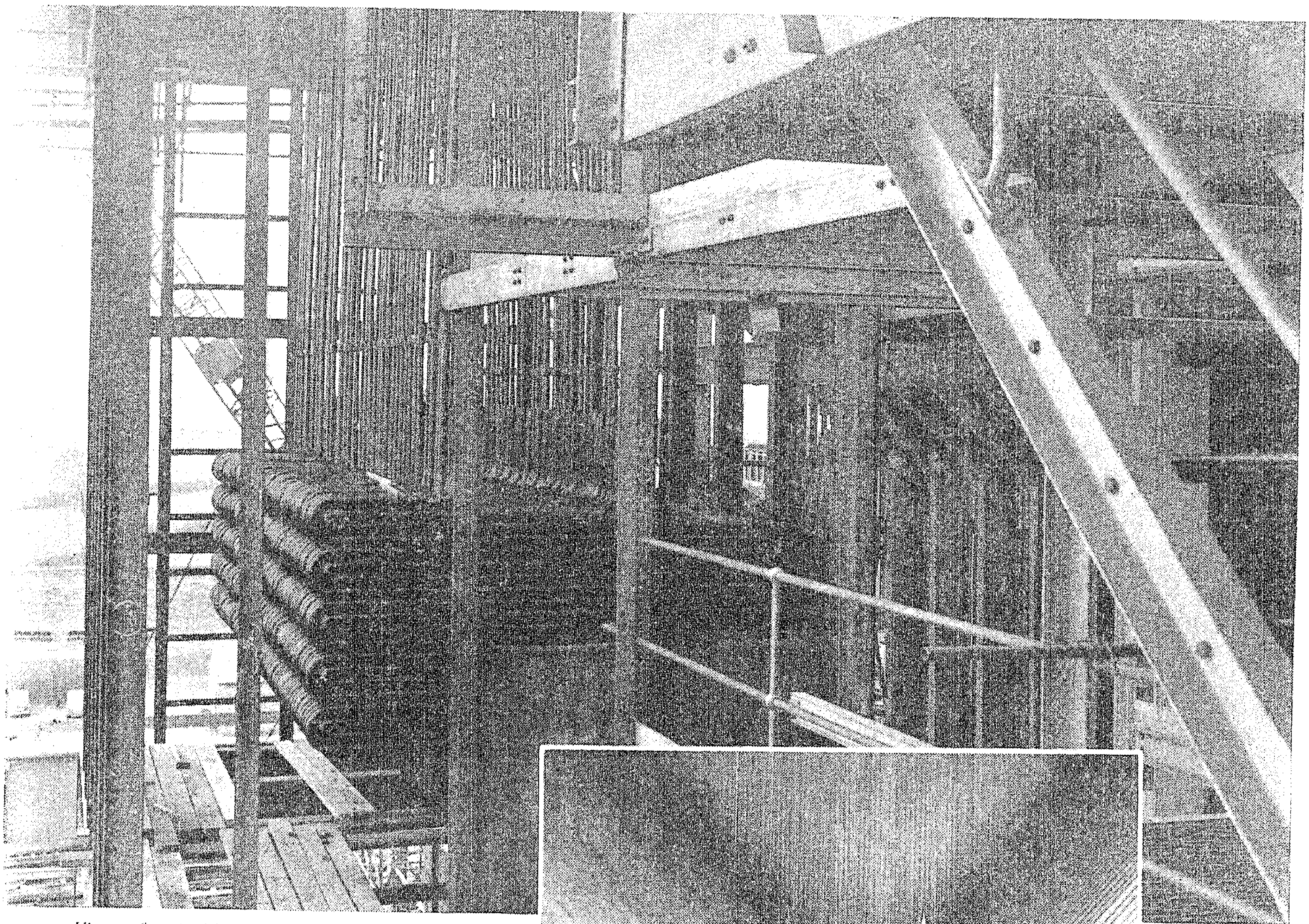

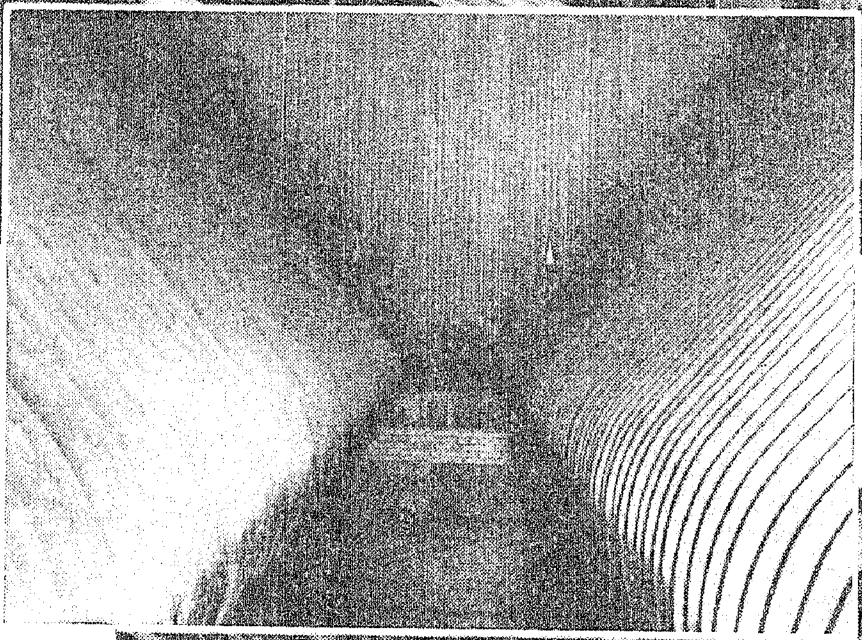

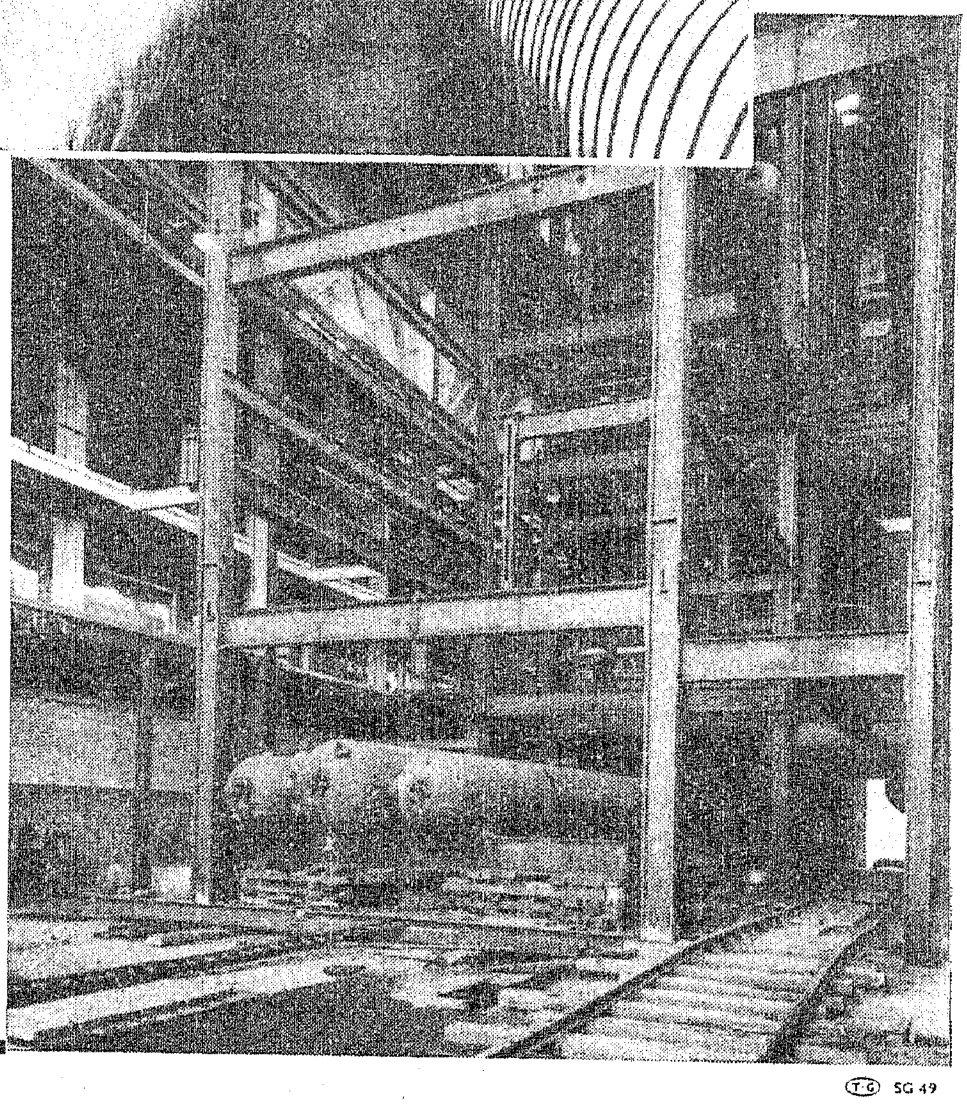

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Part A. POWER ENGINEERING, JUNE 1955

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